SECTION 2

ADVANCED
PRACTICAL
RADIO ENGINEERING

TECHNICAL ASSIGNMENT

RECEIVING ANTENNAS—PART II

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RECEIVING ANTENNAS—PART II

RADIO WAVE PROPAGATION
RECEIVING ANTENNAS—PART II

INTRODUCTION.—The theory of radio wave propagation has already been presented, and several types of receiving antennas have been discussed. This assignment will deal with various types of receiving antennas, both directional and non-directional types.

THE RHOMBIC ANTENNA.—Another type of directional antenna whose action is similar to that of the Beverage wave antenna is the rhombic antenna developed by the Bell Telephone Laboratories for short-wave transmission and reception over long distances. It is shown in its usual horizontal position in Fig. 1, where its rhombic (diamond-shaped) form may be noted. It is a simple structure to design, build, and maintain. As shown, it is supported on four wooden poles on the order of one wavelength in height, and each side of the antenna may be from 4 to 10 wavelengths long. Where land is not too expensive the area required for it is reasonable, and its relatively low height makes its cost low for use in the short-wave range.

Its electrical properties are particularly attractive. It exhibits a relatively sharp directional pickup in the direction shown, and practically no pickup in the opposite direction, and yet is much simpler in every respect than the arrays of equivalent performance shown in a previous assignment. Furthermore, it maintains its directional characteristics over as much as a 2-to-1 frequency range, whereas practically all arrays function properly at one frequency only. This frequency range characteristic

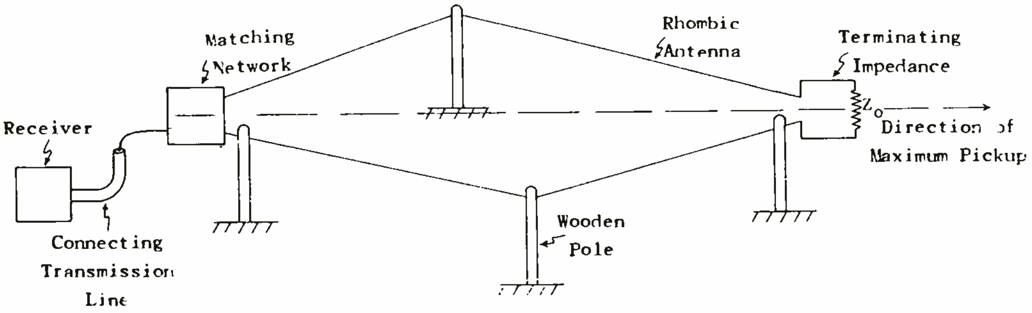


Fig. 1.—Typical rhombic antenna developed for short-wave transmission and reception by the Bell Telephone Laboratories.

is particularly important for receiving purposes, as it may be necessary to change the frequency of long distance transmission from time to time owing to variations in the ionosphere's properties. Furthermore, one antenna may be used simultaneously to pick up as many as ten different channels to feed to as many receivers.

PERPENDICULAR ANTENNA.—The action of the antenna can be understood by studying first the pickup characteristic of one side, then of two sides forming a V-Antenna, and finally of all four sides.

Consider, for example, an antenna λ in length, and *perpendicular* to the wave direction, Fig. 2. All parts of the antenna are cut simultaneously by the wave, and so in all parts alternating voltages are induced that are equal in magnitude and phase, as shown in the first column to the right of the antenna diagram. These voltages cause two sets of currents to flow in the wire: one set *toward point* 5, the other *toward point* 1. Thus, the voltage induced by the wave at point 3 causes a current to flow downward to point 5, and another current upward to point 1. Similar currents are caused to flow at other points.

The radio receiver is assumed connected between point 5 and ground, and R represents its input impedance. The set of currents flowing toward point 5 will thence flow through R and produce the input voltage for the receiver. If R = Z_0, the characteristic impedance of the line, then no reflections will occur at this point and the voltage will be simply the vector sum of the currents times R.

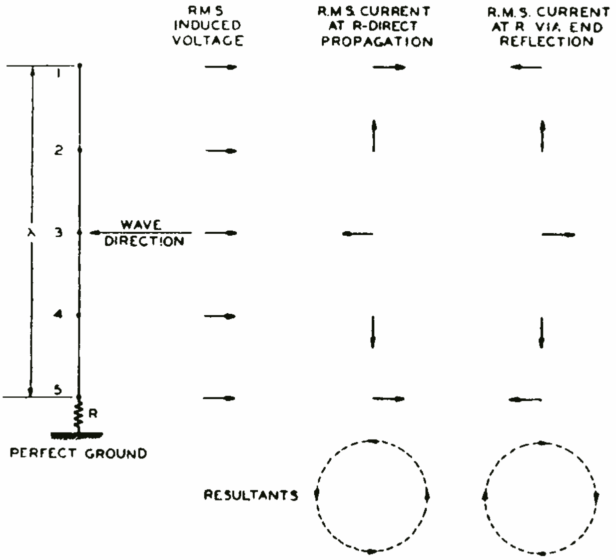


Fig. 2.—Pickup characteristics of a vertical antenna when perpendicular to the wave direction.

Similarly, if point 1 is connected through Z_0 to ground, the currents flowing toward that end will be absorbed, no reflections will occur back from the point 1 to point 5, and thus these currents will have no effect upon the voltage developed at the input terminals of the receiver. This assumption will be made, although the termination of point 1 in Z_0 would be awkward in in the above example. However, such termination of the far end of the antenna structure is quite practicable in the case of the complete rhumbic configuration, as may be noted from Fig. 1.

The currents produced in the wire are in phase with the voltages producing them at their point of origin, but as the currents proceed down the wire, they experience a time delay depending upon the distances they have traveled. Current starting from 1 has to travel a whole wavelength before reaching point 5; it undergoes a 360° lagging phase shift with respect to the voltage producing it. Current from point 2 undergoes a 270° lagging phase shift; current from point 3, 180°; current from point 4, 90°; and current from point 5, 0°, of course, since it has no distance to travel.

The second column to the right shows the vector relations, with respect to the voltages producing them, for the currents *at the time of their arrival at R.* It also represents the phase relations between the various currents. The resultant of these currents at R can be found very simply by the method described in an earlier assignment for the polygon of forces: the vectors are laid off end to end, and the resultant is the vector that joins the end of the last vector to the beginning of the first one, i.e., the one that completes the polygon formed by the vectors.

For a full-wave antenna it will be observed that the resultant is zero., or the vectors themselves complete the polygon. It is to be noted if the voltages are assumed to be concentrated at points 1, 2, 3, and 4 and 5 instead of being *uniformly* induced throughout the antenna then the polygon of vectors is a square, but if the more correct assumption is made that each infinitesimal length of the antenna gas a infinitesimal voltage induced in it that differs in phase from neighboring voltages by infinitesimal angles, then a circle of vectors is obtained instead of the square. In either case the resultant is zero; no signal is furnished to the receiver.

On the other hand, if the antenna is only a half-wave in length, i.e., if voltages from points 3 to 5 alone are considered, then the currents at R form a semi-circle of vectors, whose resultant is the diameter, as shown. This is the maximem length the resultant can have, hence an antenna greater or less than λ/2 gives less input to the receiver than one just a half-wave in length. The criterion is the length of the resultant: any means *that makes it the diameter of a semicircle will produce maximum output.* Thus, if by some means the full-wave antenna can be made to yield a *semicircle* of vectors instead of a *circle,* maximum output will be obtained.

The circle of vectors was produced because the currents from 1 to 5, upon their arrival at R, were shifted in phase with respect to one another by amounts that totaled 360°, thereby producing a full circle. If the current at 5 can be made to lag its above position by 180°, it will lead that from 1 by 180°, instead of 360°, and for the entire set of currents the vector diagram will be a semicircle instead of a full circle. This is a general requirement: the current from the far end of the antenna must lag that from the near end by not more than 180° net, by the time it reaches the near end. The word net means that the current can actually lag by *several times 360° plus another 180°*, and still give rise to a semicircle.

To obtain this net 180° phase difference between the currents from the extreme ends, recourse is had to shifting the phase of the induced voltages. Thus, if the voltage at 5 can be made to lag that at 1 by 180°, the current from 5 will have its 360° lead over that from 1 cut down by the same amount, and thus will result in the desired net phase difference of 180°.

THE INCLINED ANTENNA.—The simplest way to shift the phase of the voltages is to *incline the wire with respect to the wave direction.* In Fig. 3 is shown the configuration, the induced voltage and the current vectors. The student should note that the wave reaches point 5 a half-cycle later than point 1 because 5 is λ/2 farther away. By this simple means the voltage at 5 is 180° behind that at 1, as may be noted from the column of voltage vectors. From this it is evident that the current vectors shown in the next column will have a net phase shift of 180° from points 1 and 5, so that the polygon is a semicircle, with a maximum resultant equal to the diameter.

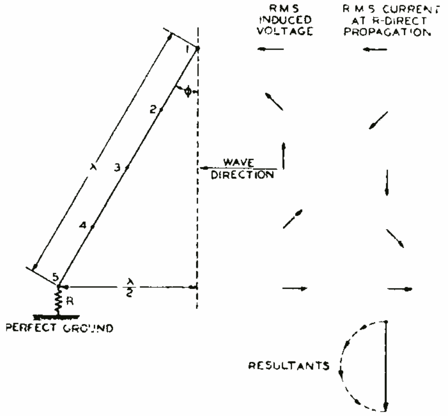
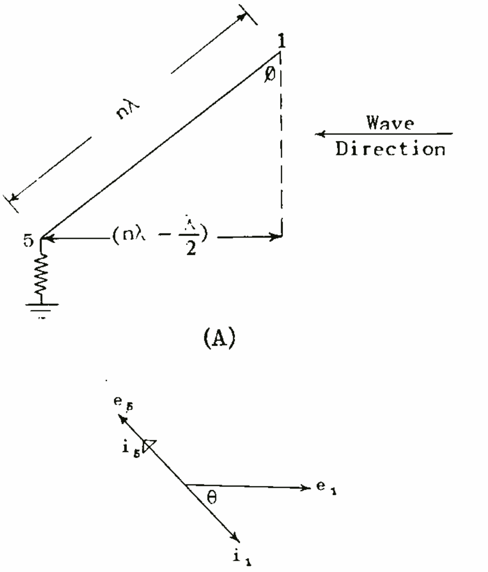


Fig. 3.—Maximum input to receiver is obtained when the antenna length is λ/2 longer than its projection upon the wave direction.

A general rule can now be evolved: *if the wire length is one-half wavelength longer than its projection upon the wave direction. maximum input to the receiver is obtained, i.e., the resultant is the diameter of a semicircle of vectors.* This can be seen very simply. Suppose the voltage induced at point 1, Fig. 4(A), is represented by vector



(A)

(B)

Fig. 4.—Condition of maximum input to receiver explained with vectors.

e_1 in Fig. 4(B). The current i_1 it produced is in phase with it at point 1, but by the time it has reached point 5, n wavelengths away (where n is any positive number not necessarily an interger), i_1 has shifted in phase by some angle θ corresponding to $n\lambda$. Now consider the voltage e_5 and the current i_5 at point 5. They are in phase and i_5 has no farther distance to travel to get to R. If e_5 is shifted in phase with respect to e_1 by 180° less than i_1 has been shifted, it will appear as shown, and i_5, in phase with it, will therefore by 180° out of phase with i_1. This will give rise to a semicircle of vectors, since all currents in between points 1 and 5 will have been shifted by lesser amounts than i_5. Therefore point 5 must be $\lambda/2$ (corresponding to 180°) less distance from point 1 *along the wave direction than along the wire direction.*

If the wire is 10λ long, then its projection should be 9-1/2 λ in length. In the example of Fig. 3, the wire is λ in length, hence its projection is $\lambda/2$, as shown. It is evident from this rule that a wire cannot be inclined at the proper angle for waves arriving from various direction. This will be analyzed in conjunction with Fig. 5. Here AB represents the wire antenna, W_1 represents one wave direction, and W_2 another. Suppose AB - AC equals $\lambda/2$, and that AB - AD is somewhere between $\lambda/2$ and λ in value. Then W_1 is the direction furnishing maximum input to a receiver connected to point A, and W_2 is a direction furnishing less input.

This indicates how such an antenna can be directional. The directivity can be further increased by making the antenna longer. Thus, if AB represents many wavelengths, then AC will also be in the order of several wavelengths. If now the direction of the wave shifts but a small amount from W_1, the projection AC will change *proportionately* but a small amount too, but the *actual* change can in itself by $\lambda/2$ if AB, and hence AC, are many wavelengths long. Thus, for a long antenna (measured in wavelengths), a small angular deviation from the direction of maximum pick-up will cause the receiver input to decrease greatly, and this is, after all, one way of defining directivity. Another advantage of a long antenna is the increase in induced voltage and hence increased gain.

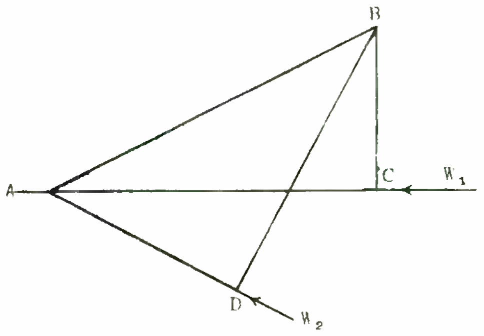


Fig. 5.—A simple inclined antenna can be very directional; here, the antenna A-B favors direction W. Directivity is increased by increasing the length A-B.

The optimum direction is usually defined in terms of the angle ϕ shown in Fig. 3. This angle is actually the one that the antenna makes with the wave front surface, rather than with the wave direction which is perpendicular to the wave front surface. However, it defines the direction of maximum pickup in that the angle the antenna makes with the wave direction is simply 90° - ϕ, i.e., the complement of ϕ.

THE V-ANTENNA.—The inclined wire can be developed into the V-type as shown in Fig. 6. The vector diagram is self-explanatory: only one additional factor enters in, that if the voltage induced in space acts at some instant—for example, in a downward direction—then it acts towards R in wire 1, but away from R in wire 2. Hence the voltage vectors *for wire* 2 must be reversed with respect to the space voltage vectors. It is evident from the diagram that each wire produces a resultant voltage, the vector of which is a diameter (hence a maximum), and the two are in series aiding.

If the wire 2 were in line with 1, then the above phase reversal would not have occurred and the two resultants would have been in series opposing. For the V-antenna, each wire should exceed its projection on the wave direction by $\lambda/2$ for maximum output, so that the tilt angle ϕ for either should be the same.

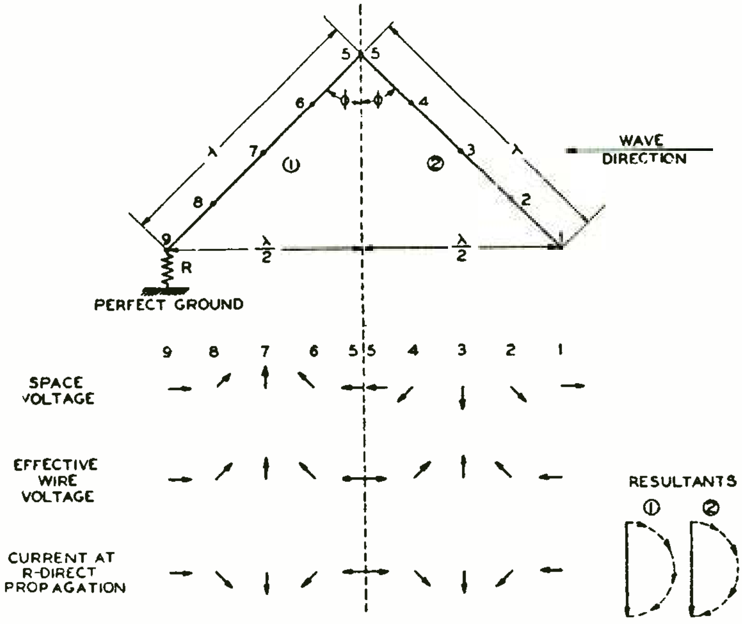


Fig. 6.—A V-antenna has more output and directivity than a single inclined antenna; in addition, the direction of optimum pickup remains substantially unchanged over a range of frequencies.

The V-antenna has at least three advantages over the single inclined wire:

1. It requires no additional poles, yet has more output and directivity.

2. Since both ends are near ground, it becomes possible to terminate each to ground in Z_o through short connections that will have negligible voltages induced in them by the impinging wave.

3. Departures from the opti-

mum value of ϕ tend to balance in the V-antenna for the following reason. The optimum value of ϕ can be found from the relation between wire length and projected length. Thus, referring to Fig. 3, we note that

$$\sin\phi = \frac{\text{Projection of wire along wave direction}}{\text{Length of wire}} = \frac{n\lambda - \lambda/2}{n\lambda}$$

$$= \frac{n - 1/2}{n} = \frac{2n - 1}{2n}$$

This relation can be plotted, i.e., ϕ versus n, where n is the multiple of a wavelength that represents the wire length. The plot is shown in Fig. 7. It will be noted that ϕ changes very little with n when n is greater than 6 or 8. But as was shown that a long wire does not require much change in Wave direction or in ϕ to produce an appreciable change in receiver input. Hence for a long single wire antenna it can be expected that the pickup will vary appreciably with frequency, or that the direction of maximum pickup will change somewhat with frequency.

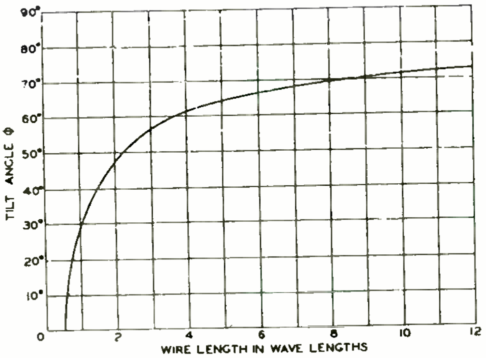
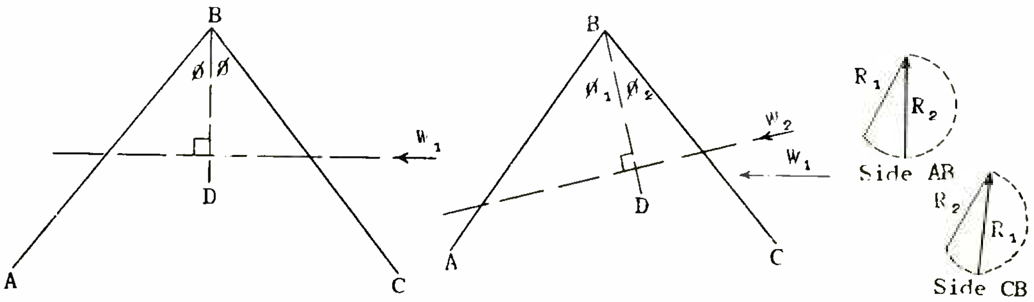


Fig. 7.—Plot of optimum tilt angle (ϕ in Fig. 3) required for any given length in wave lengths of a single inclined antenna.

The variation of the direction of maximum pickup does not occur for a V-antenna because of the balancing effect of the two wires. In Fig. 8(A) is shown a V-antenna such that ϕ is optimum for wave direction W_1. This means that the projection of either AB or BC on W_1 is $\lambda/2$ less than AB or BC. Now suppose the frequency is raised (λ decreased). From Fig. 7 it is evident that ϕ should be increased. Suppose this is done for AB by changing to the wave direction W_2, [(Fig. 8(B)]. This increases angle ABD from ϕ to ϕ_1, but it simultaneously decreases angle DBC from ϕ to ϕ_2. Note that ϕ, ϕ_1, and ϕ_2 are in all cases the angle included between the corresponding side and the line BD *perpendicular to the wave direction.* The resultant of the vectors for AB is lengthened somewhat from R_1 to R_2, but that for CB is shortened to a greater extent from R_1 to R_2, as shown in Fig. 8(C). The overall output is therefore decreased. In short, the greatest output is still obtained for direction W_1 even though either angle is less than the optimum value of ϕ_1. *Thus, the direction of optimum pickup remains substantially unchanged over a range of frequencies.*

ASYMMETRICAL DIRECTIVITY.—The antennas described above can be made to have a nearly complete null in the direction opposite to that of maximum pickup over a considerable frequency range. The antenna is then said to have asymmetrical directivity. The vector conditions that produce this effect are shown in Fig. 9 for a V-antenna. The vector diagram is shown for one of the wires; that for the other is similar and directly additive to the first-mentioned. Note how the vectors form a semicircle (resultant a maximum) for the front wave, and how they form a complete circle (re-



(A) (B) (C)

Fig. 8.—Example of balancing effect of a V-antenna.

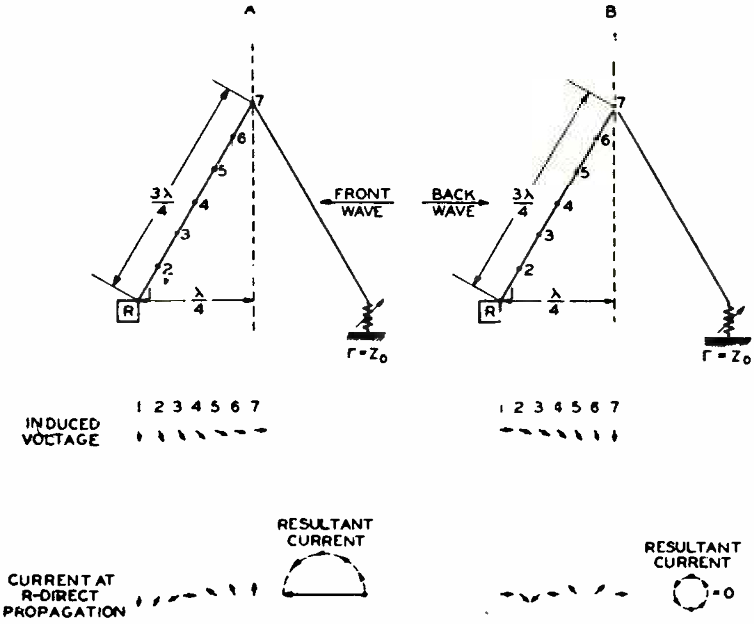


Fig. 9.—Asymmetrical directivity of a V-antenna explained with vectors.

sultant of zero) for a wave in the opposite direction (back wave). This condition occurs when the wire length of each element is an odd integer multiple, greater than one, λ/4. The optimum tilt angle previously given must still be maintained.

For example, in Fig. 9, the wire length of either side is the odd integer *three* times λ/4 or 3λ/4. At the same time, the projection along the wave direction is λ/4, which is λ/2 less than 3λ/4. Suppose the wire length were 6λ. This would be 6 × 4 = 24 times λ/4 and would be unsatisfactory, since 24 is an even integer. But if the wire length were 6-1/4, then it would be 25 × λ/4, which is an odd integer multiple and satisfactory. The projection along the wave direction would have to be 6-1/4λ - λ/2 = 5-3/4λ for maximum pickup.

It is evident that a change of frequency and consequent change in λ may make an antenna depart from the rule just given, and so the antenna will no longer exhibit asymmetrical directivity. However, if the antenna is many wavelengths long, it will have a high ratio of front-to-back pickup even where its length is an even multiple of λ/4 instead of an odd multiple. The ratio of front-to-back voltage pickup versus λ is given in Fig. 10. It will be noted that for a wire length of 5λ, for example, the front-to-back voltage ratio is as high as 19 to 1, which is usually more than sufficient for most practical purposes. Note also from the figure that for a wire length of 4-3/4λ, the ratio is theoretically infinite, as is to be expected, since 4-3/4λ is 19 times λ/4, i.e., an odd integer multiple of λ/4.

If slight readjustments are made in the terminations to the antenna, the set of currents traveling along the antenna *away* from the receiver are no longer completely absorbed at the far end, and their reflection can be used to cancel the small amount of back signal when the wire length is an even multiple of λ/4. If the wire is an even multiple of λ, four or higher, the modified termination is given by

$$Z_o' = Z_o \cos (90^\circ - \phi)$$

where Z_o is the characteristic impedance of the antenna. For example, if the length of a side is 10λ, then from Fig. 7 we find ϕ to be 72°, from which cos (90° - 72°) = cos 18° = .95. This means that the termination need be reduced by only 5% from the normal characteristic impedance value. In practice a compromise value between the above modified value Z_o is chosen, so as better to accomodate a range of fre-

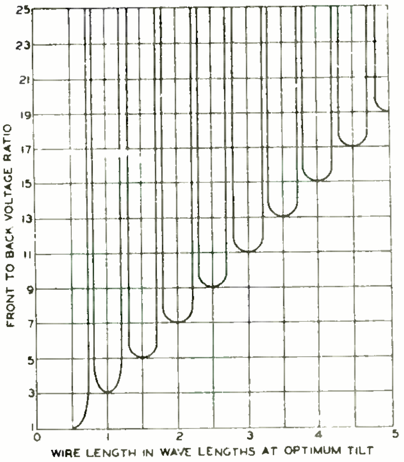


Fig. 10.—Ratio of front-to-back voltage pickup versus wire length in wave lengths.

quencies.

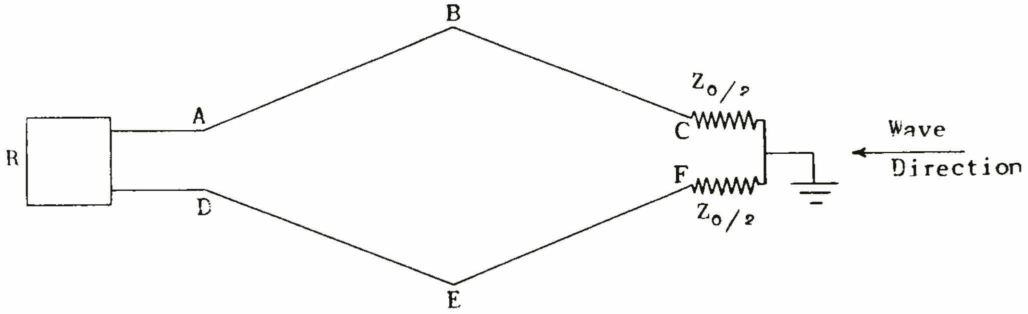


Fig. 11.—A rhombic antenna can be regarded as two V-antenna in series.

THE RHOMBIC ANTENNA.—The V-antenna can be extended to form the rhombic structure, since the latter can be regarded as two V-antennas in series. It will be recalled that the two sides of the V-antenna have voltages induced in them of opposite phase with respect to the receiver because of their opposite tilt. By the same token the voltage in AB, Fig. 11, is opposite in phase to that in DE, and that in BC is opposite to that in EF. Thus the voltage from *either V* is the same in magnitude, or the rhombic antenna is *balanced to ground* so that *no ground current flows from* either termination $Z_0/2$. The two halves can be made into one resistor Z_0, and the ground connection shown in Fig. 11 can be removed if desired. This makes the rhombic antenna independent of variations in ground resistance with weather—an important practical consideration. In addition, the output and directivity are greater than that of a V-antenna.

The termination in the case of a receiving antenna can be a small low-wattage carbon type of resistor, but in the case of a transmitting antenna it must be much larger, since it must be capable of dissipating between 25 and 50 per cent of the transmitter power. For such purposes special antenna resistances are today being manufactured. For very large powers a special type is employed in the form of a long iron-wire transmission line. This has such a high dissipation that it acts substantially as a pure resistance even if the far end is merely short-circuited instead of terminated in its characteristic impedance, as there is very little energy left at the far end to be reflected. Furthermore, its long length enables it to dissipate large amounts of energy.

The rhombic antenna is almost exclusively employed with its plane horizontal to the earth for the following reasons:

1. Four relatively short poles, all of equal height, are required. This is a comparatively cheap supporting structure.
2. It is responsive for low

vertical angles mainly to horizontally polarized waves. For long distance transmission via the ionosphere, the waves arrive with about equal horizontal and vertical polarization, so that either *provides* about equal signal intensity. But the horizontally polarized component is less affected by varying ground constants, and hence the performance of the horizontal antenna is more stable under varying weather conditions.

3. The direction of wave propagation is more nearly constant in the horizontal than in the vertical plane, hence an antenna inherently more directive in the horizontal than in the vertical plane is desirable. The rhombic antenna possesses such a characteristic.

4. The rhombic antenna has a directional characteristic in the vertical plane, i.e., in a plane at right angles to the plane of its wires. At some angle Δ to the horizontal it has maximum pickup. This angle can be varied to some extent by varying its tilt angle ϕ, and thus the direction of maximum pickup in the vertical plane can be made to coincide with the downward angle of the sky wave.

5. At lower frequencies the downward angle of the sky wave tends to be greater, i.e., the sky wave comes down to earth at a steeper angle. The rhombic antenna's vertical angle of maximum pickup Δ, tends to be greater at lower frequencies and the directive pattern tends to become broader as well. Thus this antenna is very well suited for long distance reception and transmission *over a range of frequencies.*

6. The pickup of a horizontal rhombic antenna spaced a wave length or so above earth tends to be zero in the horizontal plane. It will be recalled from an earlier lesson that the image of a horizontal antenna above ground is the same distance below ground, and has a current flowing in it equal but opposite to that flowing in the actual antenna. Hence the radiation to any point on the ground from the antenna and its image cancel, and by the *reciprocity* theorem mentioned in a previous assignment, the pickup of the system when functioning as a receiving antenna is zero, too. As a consequence of the above, pickup of ignition, power, and other noises originating near the ground is practically zero, the more so since these disturbances are mainly vertically polarized, and the horizontal rhombic is not responsive to them.

DESIGN CONSIDERATION.—If the rhombic antenna were located in free space, its radiation (or pickup) would be a maximum in the direction of its longest diagonal (see Fig. 1). Owing to the effect of the ground, the horizontal rhombic antenna has zero pickup in the horizontal plane represented by earth—halfway between it and its ground image. However, at some (vertical) angle to the plane of the earth, and in the same horizontal direction as its longest diagonal (principal axis), its pickup is a maximum.

In Fig. 12(A) is shown a plan or top view of the antenna, and in 12(B) is shown a side view. In (A) maximum pickup occurs for a wave direction along the principal axis (β = 0). But the angle that this wave must make *with the plane of the antenna* and hence with the earth beneath it, to obtain maximum pickup is for some angle Δ, as indicated in 12(B). (Thus β represents the horizontal angle of the incoming wave with respect to the longer R axis of the antenna and Δ represents the vertical angle with respect to the plane of the antenna. If the plane of the antenna is horizontal, Δ also represents the vertical angle at which the wave approaches the earth).

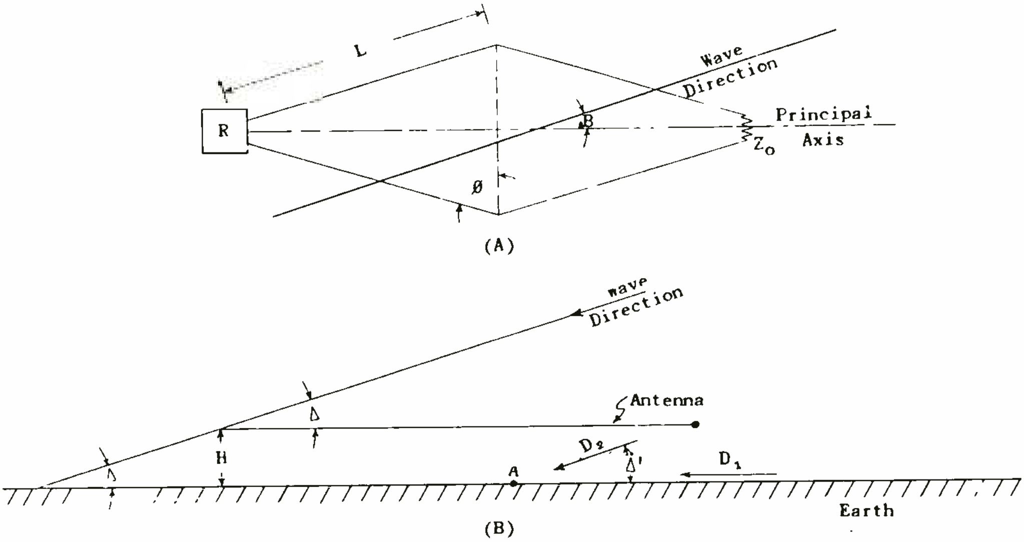


Fig. 12.—Top and side view of a rhombic antenna. Maximum pickup will be obtained at some angle Δ.

The student must remember that in speaking of the directivity of a receiving antenna, one has in mind the reception of radiation from all around the antenna on a sphere so large that the antenna and its ground image appear but a point at the center of this sphere when viewed from any of the points on the surface.

The antenna and its ground image can therefore be regarded as concentrated in a point directly beneath the actual antenna, and all waves regarded as directed to this point. This point is represented by A in Fig. 12(B). Waves coming from points in the plane of the earth have directions like D_1. The vertical angle of D_1 is the angle between it and the earth's plane, and this is clearly zero, i.e., angle Δ in this case is zero. The horizontal angle is the angle that D_1 makes with the direction of the principal axis, and one such angle is represented by β in Fig. 12(A). Evidently for radiation from points in the plane of the earth. Δ is zero, but β may be any value from zero up to 360°.

On the other hand, consider a wave coming from a direction D_2 toward A, and making the vertical angle Δ_1 to the plane of the earth. If D_2 is swung around A as a pivot while angle Δ_1 is maintained constant, a cone will be generated by D_2. For different values of the vertical angle, different cones will be generated. Thus a line from A having some horizontal angle β and some vertical angle Δ can be drawn to represent radiation coming from any desired distant point. The signal output of the antenna for radiation coming from such a direction can be represented by drawing a line from A at the corresponding values β and Δ, and of such length as to represent the signal output to some scale.

This will form a directivity pattern as discussed in previous assignments. Note, however, that such a pattern for *all* values of β and Δ represents a *surface in three dimensions*, rather than a curve drawn in one plane. Since it is inconvenient to draw such a surface on a sheet of paper, cross-sections of the surface are drawn instead. One such cross-section can be that produced by a horizontal slice of the surface, another by a vertical slice of the surface. Or, an irregular slice of the surface can be made such that all points involved have the same angle Δ, or the same angle β. It is evident that an almost bewildering set of curves can be obtained from the surface representing a plot of the complete special directional characteristics of the antenna.

In the present instance we shall be interested primarily in one particular horizontal and one particular vertical cross-section. The vertical cross-section will be a vertical plane passing through the principal axis of the horizontal rhombic antenna. The resulting directional patterns are shown in Fig. 13 in the right-hand half of the diagram for various frequencies, (values of λ) and show the pickup vs. the angle Δ.

The horizontal cross-section chosen is that of the earth, i.e., a plane through point A of Fig. 12. The curves shown in the left-hand half of Fig. 13 are for various frequencies and represent the pickup vs. the angle β. A word of explanation is necessary at this point. The horizontal pickup corresponds to directions in the plane of the earth, such as D_1 of Fig. 12(B). Actually the pickup in this plane is zero, for the ground image acts in a manner to cancel the pickup of the actual antenna itself, just as in the case of a transmitting antenna. Thus the curve should be merely a single point, representing radius vectors all of zero length for all values of β. The curves actually shown in Fig. 13 are for a rhombic antenna *in free space*, in which case no image is present to produce a canceling effect, and the curve is that for the plane of the antenna.

However, the curve obtained for a horizontal rhombic antenna near the earth, when the horizontal cross-section of the directional surface is not the plane of the earth, but *above* it (so that angle Δ for the points of the curve is other than zero), is so close in shape to the free-space pattern in the plane of the antenna, that the latter may be used to illustrate the former, and is somewhat easier to calculate.

Thus, the upper set of curves indicate what pickup may be expected for waves coming at the antenna from various horizontal directions.

It will be noted that the direction of maximum pickup remains over the frequency range along the principal axis, as was explained previously.

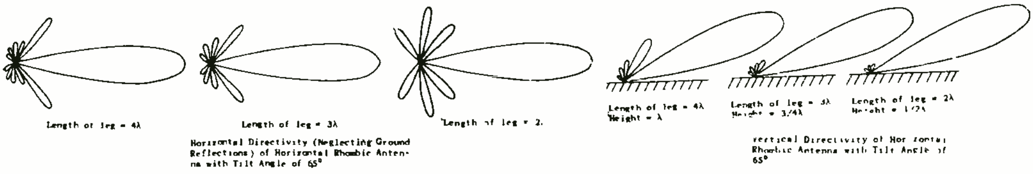


Fig. 13.—Top and side views of directional patterns for various frequencies.

It is therefore a simple matter to align the antenna with the great circle along which the wave is traveling from the transmitting point *without having to take the frequency into consideration.*

The lower curves of Fig. 13, on the other hand, indicate that the angle Δ of the maximum pickup increases with λ, i.e., as the frequency decreases, or—what is equivalent—as the length L of the sides is decreased. Since the vertical angle of maximum pickup is sensitive to frequency, and since this angle should coincide with that of the sky wave to be picked up, the rhombic antenna is designed so that its dimensions and proportions furnish maximum pickup at the vertical angle of the sky wave, and as for the horizontal angle of the sky wave, the antenna is oriented so that the principal axis lies along the great circle of the earth passing through the receiver and transmitter locations.

Under these conditions the height, length, and the optimum tilt angle are given by the following expressions:

$$H = \frac{\lambda}{4 \sin \Delta} \qquad (1)$$

$$L = \frac{\lambda}{2 \sin^2 \Delta}$$

$$\sin \phi = \cos \Delta$$

where Δ is the vertical angle that the sky wave makes with the horizontal (earth). This angle varies with frequency, and is smaller, the higher the frequency. Unfortunately, it also varies with the time of day and with the season owing to variations in the ionosphere, and a longer cycle of variation probably is also present. Hence the antenna should not have too sharp a lobe in the vertical plane.

Suppose it is found, on the average, that the wave to be received (assuming a 15 mc frequency) arrives at an angle of 10°, with a range of variation from 5° to 15°, so that $\Delta = 10°$. The wavelength is

$$\lambda = \frac{3 \times 10^8}{15 \times 10^6} =$$

$$20 \text{ meters} = 20 \times 3.28 = 65.6 \text{ feet}$$

Then

$$H = \frac{65.6}{4 \sin 10°} = \frac{65.6}{4 \times .1736} =$$

$$94.5 \text{ feet} = 1.44\,\lambda$$

$$L = \frac{65.6}{2(.1736)^2} = 1089 \text{ feet} = 16.59\lambda$$

$$\sin \phi = \cos 10° = .9848 \text{ or } \phi = 80°$$

The length and height are rather large, owing to the low angle of 10° chosen for this frequency. The vertical directional pattern has been plotted in Fig. 14. It is based on the formula

$$I_R = k' \left[\sin\left(\frac{2\pi H}{\lambda} \sin \Delta\right)\right] \left[\frac{\cos \phi}{1 - \sin \phi \cos \Delta}\right] \left\{\sin^2 \frac{\pi L}{\lambda} (1 - \sin \phi \cos \Delta)\right\} \quad (2)$$

Here I_R is the current at the receiver terminals, k' is a constant of proportionality (arbitrarily taken as 1.6 in Fig. 14 to suit the scale of the polar graph paper, and H, L, ϕ are the values found from the preceding formulas for $\lambda = 20$ meters and a sky wave angle of 10°. In this formula Δ is the independent variable, and I_R is plotted against it in Fig. 14. A striking feature is to be noted: although the values for L, H, and ϕ found from Eq. (1) give maximum I_R for a wave angle of 10° to the horizontal, as compared to the magnitude of I_R for any other set of values of L, H, and ϕ for the same angle of 10°, nevertheless, *for these same dimensions*, if the wave arrived at about 8°, the receiver current I_R would be larger.

This appears to contradict the requirements. It would seem that the design formulas should give values of L, H, and ϕ that would produce a polar diagram having maximum pickup at 10° rather than at 8°. If, however, design formulas (to be given) are employed to make the an-

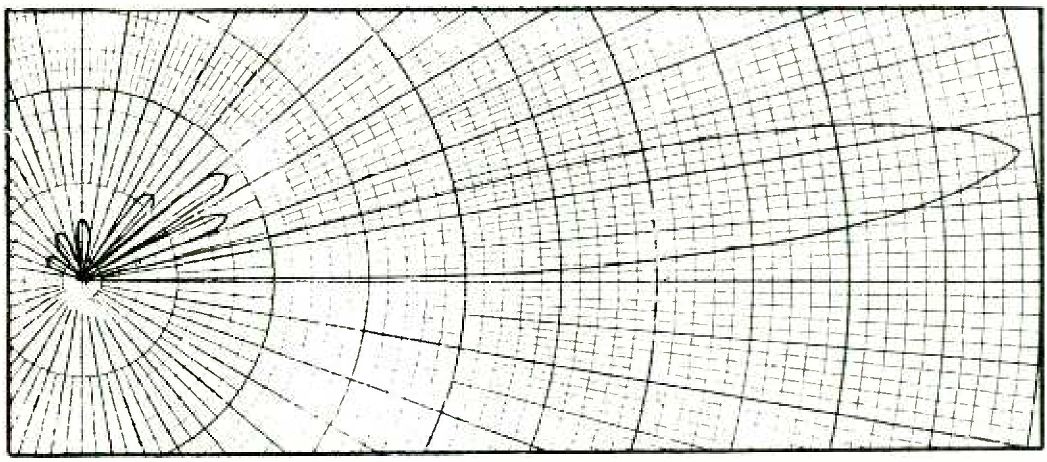


Fig. 14.—Plot of I_r versus Δ through a range of 0° - 15° (considering major lobe only) when H,L and ϕ are based on λ = 20 meters and Δ = 10°.

tenna have maximum pickup at 10° instead of 8°, it will be found that the value of I_R now obtained at 10° is *less* than the previous value.

This is shown in Fig. 15. The solid curve is a plot of Eq. (2) when the values of L, H, and ϕ appearing in that equation are determined by Eq. (1). The length OA represents the magnitude of the receiver current. The dotted curve is a plot of Eq. (2) when L, H, and ϕ are determined by Eq. (3) given below. In this case the polar diagram is aligned so that maximum pickup OB occurs in the direction of the wave. But note that OB, while greater than any other radius vector of the dotted curve, is nevertheless smaller than OA, which, in turn, is not the maximum of its curve.

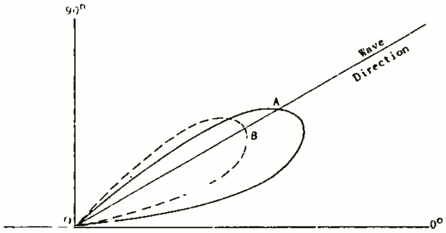


Fig. 15.—Choice of pickup pattern depends on frequency to be received.

This is an important point in the design of rhombic antennas. At the higher frequencies (above 10 mc) the *inherent receiver noise* tends to exceed the atmosphere static and hence acts as the lower limit to the magnitude of desired signal that can be profitable amplified, whereas at lower frequencies the *atmospheric static* is the limiting factor.

For this reason it is of advantage for the antenna to pick up at the higher frequencies as strong a signal as possible in order successfully to override the receiver noise, even though the antenna in so doing picks up a relatively greater amount of static. In such a case the solid curve of Fig. 15, corresponding to Fig. 14, would be preferable. The signal picked up is a maximum, but since the maximum pickup is below the wave direction, static at this lower angle will be even more favored by the antenna than the desired signal. But since static does not compare with the receiver noise at this frequency the greater pickup of static is not important, but the greater pickup of signal (OA instead of OB) is of value.

At the lower frequencies the dotted curve of Fig. 15 is preferable. Here signal-to-static ratio is the determining factor, *and from that same direction* OB equally favors the signal and static. Note that in the latter case static that comes equally from all directions is discriminated against by the directional pattern, and if it should come from the left in Fig. 15, the discrimination would be virtually 100 per cent (assuming complete asymmetrical directivity).

ALIGNMENT DESIGN.—If it is desired to align the directional pattern with the wave direction, the following relations must be used:

$$H = \frac{\lambda}{4 \sin \Delta}$$

$$L = \frac{0.371\,\lambda}{\sin^2 \Delta} \qquad (3)$$

$$\sin \phi = \cos \Delta, \text{ i.e.,}$$

$$\phi = 90^\circ - \Delta$$

It is to be noted from Eq. (3) that the only change is in the length. Reducing it to approximately 74 per cent of the value given by Eq. (1) alters the directive pattern so that maximum pickup occurs at the same angle Δ as the wave direction. As stated previously, the actual magnitude of the receiver input signal current is now less, but its ratio to the static component is greater.

For the problem given previously, the new length will be

$$L' = \frac{65.6 \times .371}{(.1736)^2} = 808 \text{ feet} = 12.31\,\lambda$$

The height remains 94.5 feet, and the angle of tilt ϕ remains 80°. The directional pattern can now be calculated from Eq. (2). The only term that changes is the third term in the right-hand expression, since this is the only one containing the length of the antenna. The resulting pattern is shown in Fig. 16.

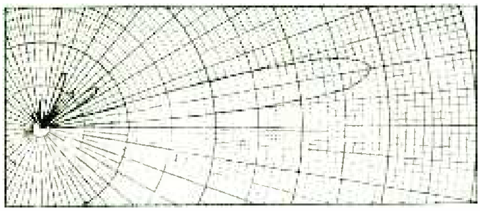


Fig. 16.—Plot of I for L = 12.31 λ.

Note that now the direction of maximum pickup coincides with the wave direction, namely, 10°, but the relative response at this angle is 7.78 as compared to 9.22 by the previous method (Fig. 14), a reduction to 84.4% of the latter value.

COMPROMISE ALIGNMENT DESIGNS.— In actual practice modifications of the preceding designs may be necessary.

(a) If, for reasons of lack of space or the like, either L or H must be changed from the values of Eq. (3), it is still possible to choose one arbitrarily, and find a value for the other which will give a directional pattern *that remains aligned with the desired vertical angle* Δ *of the incident wave*, although the signal pickup will be reduced.

If the relation $\sin\phi = \cos\Delta$ is maintained, then the relative height and length, H/λ and L/λ respectively, can be calculated from the following equation:

$$\frac{(H/\lambda)}{\tan\,[2\pi\,(H/\lambda)\,\sin\Delta]} = \frac{1}{2\pi\sin\Delta} - \frac{(L/\lambda)\,\sin\Delta}{\tan\,[\pi\,(L/\lambda)\,\sin^2\Delta]} \qquad (4)$$

This equation is so involved, however, that H/λ has been plotted versus Δ in Fig. 17 for values of L/λ from 1 to 16.

Suppose, in the preceding problem, that the height can be only λ instead of the optimum value of 1.44λ; i.e., H/λ equals 1 instead of 1.44. Then from Fig. 17, for $\Delta = 10^\circ$, L/λ must be 15 (point A), or $L = 15\lambda = 15 \times 65.6 = 984$ feet. On the other hand, if H/λ can be made equal to 1.81, then L/λ is found to

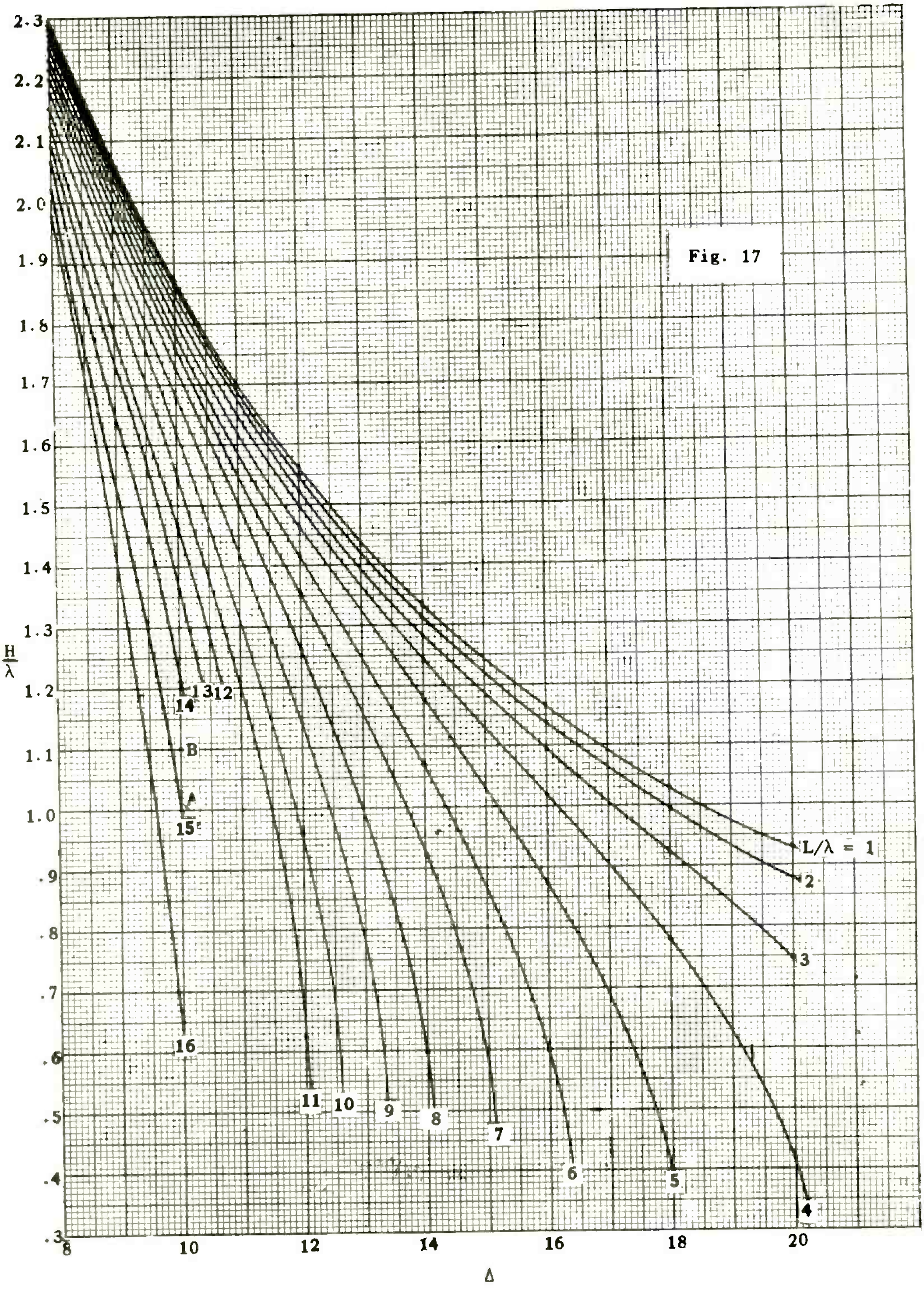


Fig. 17.—Plot of H/λ versus Δ for values of L/λ from 1 to 16.

be reduced to 5 or L = 328 feet.

Interpolations can also be made. Thus, for H/λ = 111 (point B), it is evident that L/λ must be between 14 and 15. Since there are 21 divisions between these two curves *along the 10° ordinate*, and B is 11 divisions above A, then the curve through B is for a value of L/λ equal to 15 - 10/21 = 14.52 or 14.5 for all practical purposes.

Note that at the smaller values of Δ, such as 8°, H/λ varies very little for a large variation in L/λ, so that H/λ might appear critical in adjustment. However, since the directive pattern in the vertical plane is rather broad, the shift in the direction of peak pickup owing to a small error in H/λ will not cause the pickup along the desired direction to decrease unduly.

(b) If H can be chosen to have its optimum value as given by Eqs. (1) or (3), then L can be varied from its optimum value *without changing the alignment of the pattern* provided ϕ is altered accordingly. The relation is

$$\sin\phi = \frac{L - .371\,\lambda}{L\cos\Delta} \qquad (5)$$

where L is the new length, and ϕ is the corresponding angle. For example, if in our problem H/λ remains at its optimum of 1.44 (H = 94.5 feet), but L is reduced from its optimum value of 808 feet to 700 feet, then

$$\sin\phi = \frac{700 - .371 \times 65.6}{700\cos 10^\circ} =$$

$$\frac{700 - 24.3}{700 \times .9848} = .98$$

or ϕ = 78.5°, a reduction of 1.5° from its optimum value. Note that this change in ϕ *does not change the direction of maximum pickup in the horizontal plane* because of the balancing effect of the two sides of each V of the antenna, as was discussed previously.

To summarize the above design methods, it may be noted that:

1. The maximum output method gives an antenna whose maximum voltage pickup is from 5 to 6 times that for a half-wave nondirectional antenna. This increase or gain in pickup in the desired direction can also be expressed on a db basis. Since db is ten times the logarithm of the ratio of the two powers involved, and since the power in this case is that picked up in the receiving antenna, and is therefore proportional to the square of the voltage picked up, we have

$$\text{db gain} = 10\log\left(\frac{5}{1}\right)^2 = 20\log 5 =$$

$$20\ (.6990) = 13.98 \text{ or } 14 \text{ db}$$

$$\text{db gain} = 10\log\left(\frac{6}{1}\right)^2 = 20\log 6 =$$

$$20\ (.7782) = 15.564 \text{ or } 15.6 \text{ db}$$

In other words, the maximum output method gives an antenna whose gain over a half-wave antenna averages from 14 to 15.6 db., or in round numbers, from 14 to 16 db.

2. The alignment and compromise alignment methods give somewhat smaller antenna gains. In the problem worked out above, the relative maximum voltage pickup was 7.78 as compared to 9.22 the maximum output method. This is a reduction of 1.44 from 9.22, or conversely, the maximum output method is greater in ratio of 9.22 ÷ 7.78 = 1.184 or 118.4%. On a db basis it is greater by
20 log 1.184 = 20 (.0734) = 1.468 or

1.5 db.

On the other hand, one can say that the compromise methods are 1.5 db less than, or down on, the maximum output method. Since the latter had a 14 to 16 db gain over a half-wave nondirectional antenna, the compromise methods have a

$$(14 - 1.5) = 12.5 \text{ to } (16 - 1.5) = 14.5 \text{ db gain over a half-wave}$$

nondirectional antenna. In round numbers the gain is 12 to 14 db. This is true provided the leg length of the rhombic antenna is not too greatly reduced. It is therefore advisable to work for maximum length rather than height in a rhombic antenna, if this is possible.

3. A perfect ground reflector is assumed, and hence as nearly level ground as possible should be employed. If the earth slopes, then the angle Δ of the incident wave should be computed relative to the sloping earth. The latter should be flat for a considerable distance beyond the antenna proper.

4. A horizontal rhombic antenna will pick up only horizontally polarized waves in its plane, $\Delta = 0$, and also in a vertical plane passing through its principal axis, $\beta = 0$. For all other values of β and Δ it will pick up both horizontally and vertically polarized waves, and this must be taken into account in computing its complete directional pattern.

ELECTRICAL CHARACTERISTICS.—The characteristic impedance of a rhombic antenna varies from about 800 to 600 ohms from the low to the high end of the frequency range. This makes it difficult to terminate it in a fixed value of resistance. However, if each side consists of several wires in parallel of variable separation, as shown in Fig. 18, a more constant and lower resistance of about 600 ohms is obtained. The equivalent larger conductor effect at D and E compensates for the greater spacing D to E of the antenna when viewed as a transmission line. The separation is determined experimentally.

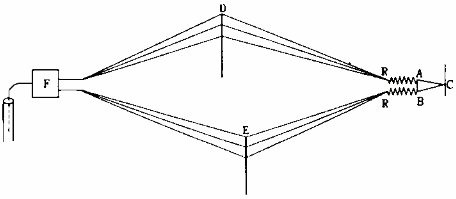


Fig. 18.—**Rhombic antenna using several wires in parallel.**

In the figure is also shown the method for obtaining a termination, good over at least a 2-to-1 frequency range. Usually the rapidly converging sides of the antenna contribute a certain amount of capacity to the two halves of the termination RR, but if they are connected as shown in the figure, ahead of the apex C, and with a wire connector AB (critically adjusted), then a satisfactory termination is obtained.

The antenna may be directly connected to the receiver (or the transmitter in the case of a transmitting antenna) through a two-wire 600-ohm line, but it is preferable, especially for receiving purposes, to employ a more carefully shielded type of line, i.e., a coaxial cable. It is therefore necessary to interpose a network F, Fig. 18, in order to match the unbalanced-to-ground low impedance cable—about 72 ohms—to the balanced-to-ground antenna. Such a network is shown in Fig. 19.

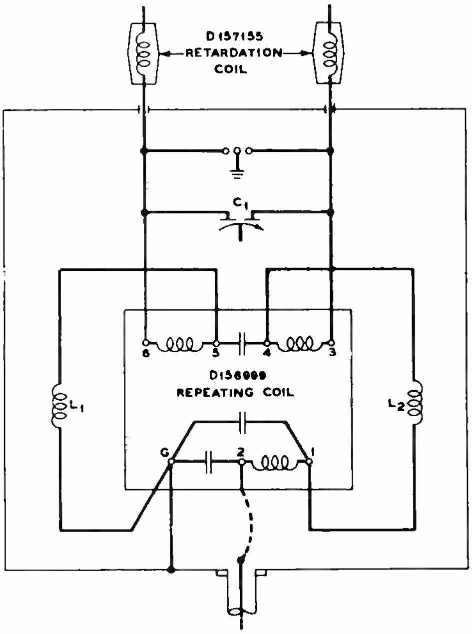


Fig. 19.—**Network to match transmission line to antenns.**

The particular circuit shown can match the cable to a *single wire* rhombic antenna whose impedance varies over the frequency range (4 to 22 mc). It employs a metallic dust core transformer, inductances to tune out any residual antenna capacity, has lightning arresters and circuits to permit the application of direct current for the maintance testing of antenna continuity.

NON-DIRECTIONAL ANTENNAS

BROADCAST ANTENNAS.—In many cases, as in most broadcast receiver installations, antenna directivity is undesirable. In the standard broadcast frequency range, where transmission throughout the primary service area is essentially by means of the ground wave, a vertical, grounded antenna is normally employed to pick up the signal, which is mainly vertically polarized.

This type of antenna is of the Marconi type and may have any one of the forms described previously: Single vertical wire, inverted L-type, T-type, etc. Such antennas show practically no directivity in the (horizontal) plane of the earth, and are well suited for broadcast pickup.

One important practical difference between a receiving and transmitting antenna is that the transmitting antenna is always tuned to the operating frequency, by lumped coils or capacitors, if necessary, whereas the receiving antenna is seldom tuned because it is generally called upon to cover a band of frequencies, and tuning to any one frequency in the band would require an extra control, to be operated independently or ganged with the other receiver tuning units.

However, the normal broadcast antenna is usually less than a quarter wave length, and may be as little as four to five feet long, as in the case of an automobile whip antenna. Such antennas exhibit mainly a capacitive reactance and do not approach resonance (quarter wave in length) in the broadcast band. They may consequently be regarded as aperiodic, i.e., as not exhibiting tuning in the frequency range of operation. The antenna may therefore be considered as a generator whose internal impedance is essentially capacitive, and whose generated voltage is ε H, where ε is the field strength in volts per meter and H is its effective height in meters. These terms have been explained in a previous assignment.

The antenna is generally coupled to the first stage of the receiver as shown in Fig. 20. The input transformer is composed of primary coil L_p and secondary coil L_s, loosely coupled. In the early days of radio broadcasting L_p was made of few turns and hence low inductance and was resonant *above* the band, so that in the band its reactance was low and the antenna current was limited by the internal impedance of the antenna itself rather than by L_p. Moreover, practically all the antenna current flowed through L_p, and only a negligible amount through the latter's distributed capacity, C_p (shown by dotted lines).

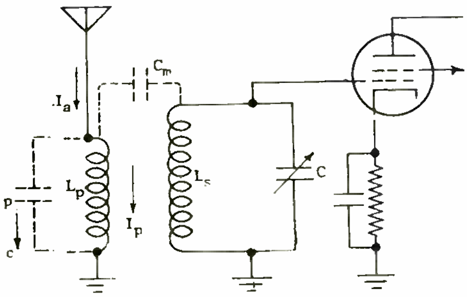


Fig. 20.—Typical input circuit of a receiver.

The voltage induced in secondary L_s is

$$e_s = \omega M I_p$$

where M is the mutual inductance between L_p and L_s, and I_p is the current through L_p, and is—as explained above—practically identical with the antenna current, I_a. The secondary was made of many turns, and thus a high step-up transformer was obtained to deliver a high voltage to the grid of the first tube. This high step-up ratio is taken care of by the value of M in the above formula. It will be noted from the above formula that as the frequency, hence ω ($= 2\pi f$) was increased, e_s went up in direct proportion if the antenna current remained constant, as is approximately the case for stations of equal strength but different frequencies.

As a result, much less voltage pickup was normally obtained at the low end of the broadcast band than at the high end. Since the frequency range is about 3 to 1, this would a db variation of

$$20 \log 3 = 20 \ (.4771) = 9.542$$

$$\text{or } 9.5 \text{ db}$$

To equalize the pickup, of late years L_p has been made much larger, indeed, often so large that in conjunction with its distributed capacity C_p it resonates below the broadcast band (parallel resonance). Above this resonant frequency, i.e., in the broadcast band, the reactance of L_p ($= \omega L_p$) goes up, and that of C_p ($= 1/\omega C_p$) goes down, so that the current I_p becomes much less than I_c, and the latter approaches more and more the line or antenna current I_a in value.

The important thing is that as the frequency goes up, if I_a is constant, then I_c approaches it in value, and I_p goes down in almost inverse proportion to the frequency. Since I_p is the current that induces the voltage e_s in the secondary coil L_s, it is clear that the decrease in I_p with frequency will tend to balance the factor ωM in the formula just given, so that e_s will tend to remain more nearly constant over the broadcast band.

The use of a high impedance primary, i.e., one of many turns that is self-resonant below the broadcast band, means that it has more turns than the secondary L_s, which tunes in the broadcast band with the aid of tuning capacitor C. This in turn indicates that the antenna transformer is now of the step-down type, and that there is therefore a loss of voltage from the antenna to the grid of the first tube. This, however, can be more than offset by modern tube and circuit design, and permits a more constant sensitivity of the receiver to be obtained over the broadcast band. As a result, the a.v.c. system is not required to equalize the gain of the receiver over the band, but merely to perform its normal function of compensating for carrier amplitude variations.

In actual practice, however, a high impedance primary tends to produce more gain at the low end of the band. This variation can be equalized very readily by providing some capacitive coupling between L_p and L_s. This is shown as C_m in Fig. 20. In practice this is provided very simply and inexpensively by placing an insulated open-circuited turn between L_p and L_s to act as a capacitor plate, coupling the end turns of the two windings together. Its effective capacity is of the order of 3 to 5 mmfds.

The secondary L_s is tuned by a capacitor C ganged to the tuning capacitors of the other stages. At the operating frequency it is therefore resonant and reflects a resistive load into the primary circuit. Similarly the primary circuit reflects its reactance into the secondary circuit, but the effect either way is negligible *because the coupling between the two coils is purposely made small. This permits antennas of widely different lengths and impedances to be employed with the receiver without the secondary circuit being appreciably affected (detuned) by such antennas.*

The location of the antenna is in all cases an important point. Regions close to power wires and to electrical devices such as sign flashers, motors, street car lines, etc., are particularly noisy, and the antenna had best be located remote from such devices even for broadcast reception. Ordinarily, if the receiving antenna is mounted at least thirty feet above all electrical conductors it will not pick up much noise. In the ordinary home or apartment house this means from twenty to twenty-five feet above the roof and well away from outside power lines.

The problem is now to bring the signal over to the receiver which is of necessity located near the power lines and other sources of noise. In Fig. 21(A) is shown an ordinary inverted L-type Marconi antenna. It will be recalled from a previous lesson on antennas that the horizontal or flat top portion of the antenna radiates very little owing to cancellation of its radiation by the corresponding ground image, whereas the vertical portion and its corresponding ground image aid each other in radiating. It was shown that the principal purpose of the flat top was to reduce the antenna impedance and amount of tuning inductance required at its base and to *increase the current amplitude near the top and thus obtain more radiation from this part.*

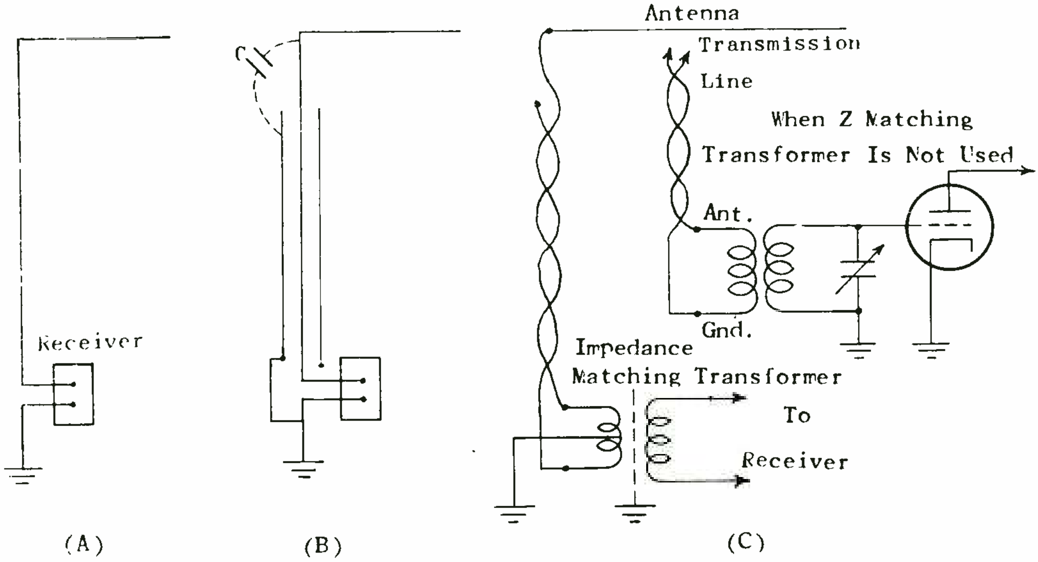


Fig. 21.—Various types of leadins.

Similar conditions obtain in the case of a receiving antenna: The vertical portion picks up most of the radiant energy, which is mainly vertically polarized, and the horizontal portion lowers the antenna's reactance and permits the generated voltage to force a greater current through the primary of the receiver's antenna transformer. However, the bottom end of the vertical portion is of necessity close to the receiver and the sources of noise; indeed, in practical cases the greater part of the vertical portion or leadin is close to noise sources.

Since, in the broadcast range a strong signal is not necessary to override set noise, the large signal picked up by the main portion of the leadin is unnecessary and in fact undesirable because of the noise simultaneously picked up. Hence a form of shielding can be employed to eliminate signal and noise pickup from at least the lower portion of the leadin, and thus only the upper portion of the leadin be permitted to furnish relatively noise-free signals. (Some signal pickup will be obtained from the horizontal portion because the impinging wave is not purely vertically polarized owing to the tilt produced by the ground losses. The horizontally polarized component of the tilted wave can produce some signal in the horizontal portion of the antenna, just as in the case of the Beverage antenna.)

If the leadin is shielded by a hollow tube as shown in Fig. 21(B), in order to prevent noise pickup at least two bad features are obtained:

1. The desired signal current will tend to flow in part through capacity C between the leadin and its surrounding shield, directly to ground instead of through the primary coil of the receiver. There is generally about a 30 to 50 percent loss of signal.

2. No noise (or signal) is picked up by the leadin, but it is picked up by the shield, and noise currents, for example, can circulate around ground, the shield, capacity C, the leadin, *and the receiver*, with the result that the noise voltages are not very effectively reduced.

In Fig. 21(C) is shown a better arrangement. Here a twisted pair act as the leadin, and neither conductor shields the other from signal or noise voltages, so that both pick up signal and noise voltages equally, particularly in view of their continual transposition. The two conductors connect to the balanced primary of an impedance-matching transformer, and thus currents flowing from the two conductors to ground cancel each other's magnetic effects in the respective halves of the primary, so that no voltage is induced in the secondary and hence no signal passed on to the receiver.

The antenna above can pass a signal mainly through its conductor of the twisted pair and thus through one half of the primary, with a resulting signal induced in the secondary. However, if there is some capacity coupling between either half of the primary and the secondary of the matching transformer, noise currents can flow directly through these to the secondary and thus appear in the output of the receiver. To prevent this, an electrostatic shield is placed between the two coils to carry off such capacity currents direct to ground. This shield, it will be shown later, also can be very effective in preventing power line noises from getting into the receiver stages. It is essential that the twisted pair be made up of good low-loss conductors, well insulated and well weatherproofed *but without metallic shielding of any sort.*

There is, however, a more important source of noise than the antenna, and that is the power line. Indeed, it is not until the noise from the latter has been eliminated that there is any great value to reducing the additional noise picked up by the antenna. It is to be expected that the power line should be a strong source of noise because the electrical loads are often the sources of such interference, as well as faulty power line insulators, and disturbances can travel for considerable distances along the line to reach the receiver.

These noise voltages act between the line and ground. The power cord is usually connected to the chassis inherently through the capacity C_1, Fig. 22, of the primary of the power transformer to the chassis, and often deliberately through relatively large capacitors C_2 and C_3. This places the chassis above ground by the noise voltage e_n. If the chassis can be grounded through a negligibly low impedance then this voltage will be shorted out. However, at the radio frequencies under consideration this is usually impossible because the receiver is practically always a considerable distance from ground and the long ground lead required, W in Fig. 22, has far too high an inductive reactance to be able to bring the chassis to ground potential.

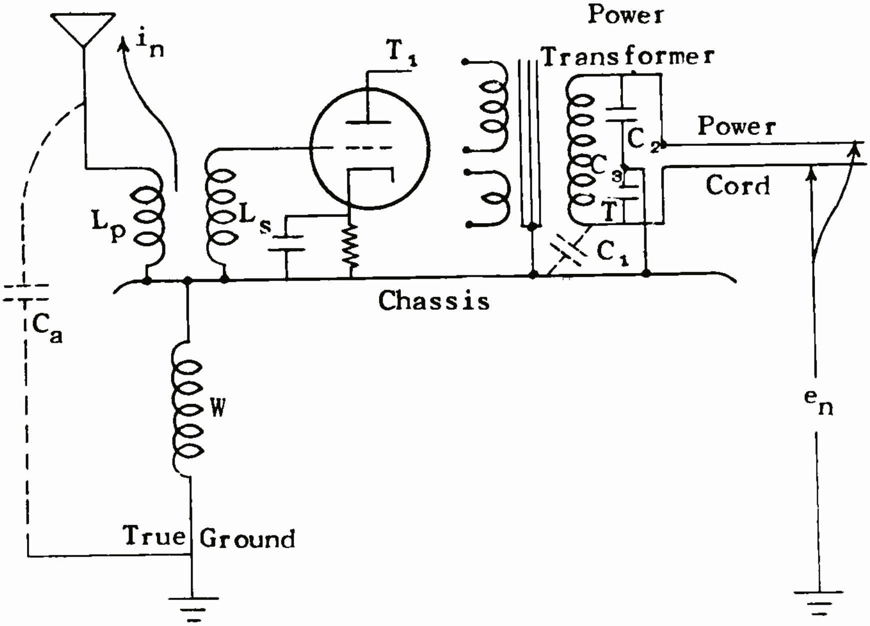


Fig. 22.—Example of noise pickup via the power line.

This does not necessarily mean that the noise voltages can get into the r-f amplifier, however. In Fig. 22 the secondary L_s of the antenna transformer and the first tube T_1 are shown connected to the chassis. The latter acts as the ground for the amplifying system, although it may be separated from true ground by the considerable impedance W. Hence L_s, and the grid and cathode of T_1 go up and down with respect to true ground by the voltage e_n. Nevertheless no portion of e_n appears *between the grid and cathode of T_1, hence there is no (amplified) effect of this voltage in the plate circuit of T_1, i.e., no effect of e_n appears in the output of the tube or succeeding tubes.*

It would thus appear that the power cord noise voltage cannot get into the amplifying circuit through direct pickup. However, notice must be taken of the primary L_p of the antenna transformer. If this is connected to the chassis, as is ordinarily the case, then a noise current i_n can flow through L_p and C_A, the capacity of the antenna to *true ground.* This current, in flowing through L_p will induce a voltage in the secondary coil L_s, and will finally appear in amplified form in the output.

To minimize this effect, the following circuit has been devised by V. D. Landon and W. L. Carlson of the RCA Mfg. Co. (A description may be found in the July 1937 RCA Review "A New Antenna Kit Design," by the above authors.) Refer to Fig. 23, where T_1 is the first tube, L_s and L_p are the secondary and primary of the antenna transformer, and e_n is the noise voltage that exists between the receiver chassis and ground. In addition three components are required: An antenna-to-line transformer whose primary and secondary are L_1 and L_2, a transmission line, and a line-to-set transformer whose primary and secondary are L_3 and L_4.

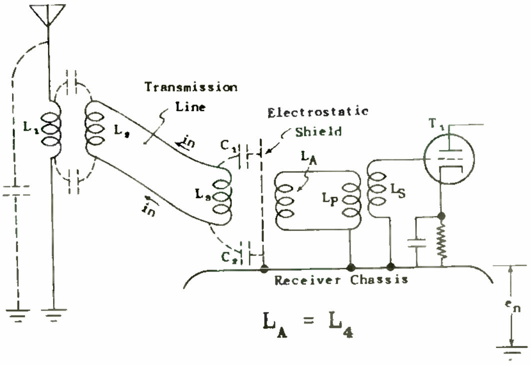


Fig. 23.—Special circuit to minimize noise pickup via the power line.

The transmission line is balanced-to-ground and is not connected to the chassis nor to true ground except through stray coupling capacities. The electrostatic shield between L_3 and L_4 eliminates any capacity coupling between these two windings and replaces such possible coupling with a certain amount of capacity coupling between the chassis and L_3, namely, C_1 and C_2. The reason for doing this is that it is easier to make the capacity coupling between the chassis and either side of L_3 equal through the use of an electrostatic shield than by attempting to arrange L_4 and L_3 properly with respect to each other and the chassis.

If the coupling to each side is the same, ($C_1 = C_2$), then the noise currents will flow in equal strength in both sides of the line in the direction shown and balance their effects in L_3, or L_2 for that matter (assuming further that the impedance from each side of L_2 to true ground is the same). Thus no voltage is induced in L_4 to be amplified by T_1 owing to an unbalanced current in L_3.

In practice there is bound to be some unbalance, but the effects can be reduced if L_3 is spaced sufficiently far away from the shield so that C_1 and C_2 are very small, for then the noise currents on each side of the transmission line will be small, and their difference—the unbalanced current—will be small indeed. Such spacing, however, tends to reduce the magnetic coupling between L_3 and L_4 to too small a value, but this can be increased to the desired value by inserting a magnetic core in the coil.

One further important point is to be noted. The antenna and leadin can be located remote from the receiver, and in a relatively noise-free region. The transmission line connecting the two is balanced-to-ground, and any noise voltages induced in it act equally in either side and balance each other as far as any current flow through L_3 is concerned. Finally, any noise voltage developed between the chassis and ground, such as in the line cord, is balanced out by the construction of the line-to-set transformer previously described.

SHORT WAVE ANTENNAS.—For picking up the short waves, and indeed, for picking up even ultra high frequencies, a doublet or Hertz antenna may be employed. This is shown in Fig. 24. The doublet is designed to have a length from extreme, neglecting the twisted or transposed leadin, of one-half wavelength at the most desired frequency. Of course a correction factor must be used as in all high frequency antenna design. This correction factor is ordinarily about .94 at frequencies below about 10 mc and about .9 at higher frequencies. Thus for best reception at 46 meters, the doublet length should be approximately:

$46 \times 3.28 \times .94 \times .5 = 71$ feet.

The factor 3.28 converts meters to feet; .94 is the correction factor necessary because an electrical impulse travels slower along a wire than through space; and .5 is used because a doublet is only one-half wavelength long. Thus in the doublet of Fig. 24 for best reception at 46 meters, each half of the doublet connecting to one end of the transmission line would be made 35.5 feet long for maximum response.

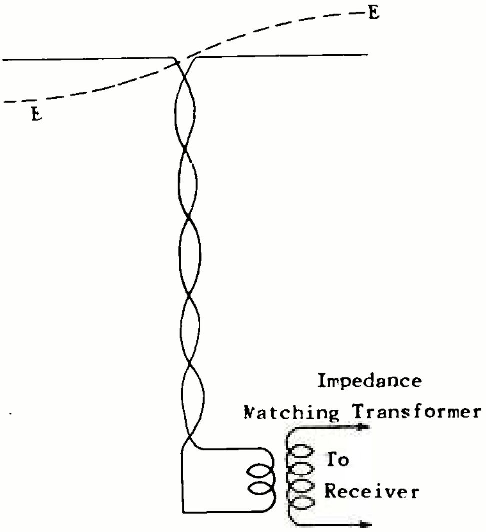


Fig. 24.—Common half-wave Hertz antenna (also called a doublet).

The input circuit of the receiver is tuned so as to present a pure resistive termination to its end of the connecting transmission line and of a value equal to the latter's characteristic impedance. There are thus no reflections at this end of the line. The antenna, however, presents an internal impedance to its end of the transmission line that varies with frequency in a manner described in a previous assignment. Thus, at its fundamental frequency (46 meters or 6,500 kc in the example just given) it looks like a pure resistance of low value—about 73.2 ohms if the mutual impedance to its ground image is negligibly small. Since the ordinary transmission line has a characteristic impedance on the order of a few hundred ohms at most, it is evident that while some reflections will take place at this end of the line, a large part of the power will be transferred to the line and thence to the receiver.

At lower frequencies the antenna has a higher, capacitive reactance, and at higher frequencies, a higher inductive reactance, and hence the power transfer to the receiver via the line will be less. When a frequency corresponding to an even harmonic of the antenna (2 × 6500 or 13,000 kc) is to be picked up, the antenna's internal impedance has risen to the order of thousands of ohms resistive, and the power transfer is poor, i.e., the reflection of power from the line back into the antenna is high owing to the large impedance mismatch.

As one preceeds to the third harmonic (3 × 6500 or 19,500 kc in the above example) the internal impedance of the antenna decreases once again to a value of about 104 ohms (neglecting the ground image) and a good impedance match and high power transfer to the receiver is again obtained. It is thus evident that the response of a doublet is peaked around its odd harmonics and is not directly suitable for wide band reception.

The bandwidth over which the antenna is reasonably flat can be extended, however, by making its conductors of large cross section. It will be recalled from an earlier assignment that the characteristic impedance of a transmission line (of which the antenna is a special example) depends upon the ratio of the conductor spacing to the conductor size. The larger the conductor, the lower is the characteristic impedance of the line or antenna and the less is the variation with frequency of the magnitude of the impedance of an antenna so constructed. Some examples will be given of this and analogous methods for extending the frequency range.

DOUBLE-DOUBLET.—To cover a broader range of the frequencies, RCA brought out the "double-doublet" with two special matching transformers, one at the antenna and one at the receiver. The double-doublet is shown (without transformers) in detail in Fig. 25. The antenna proper consists of two doublets, one having a total length of 29' × 2 = 58' and the other 16.5' × 2 = 33' connected in parallel to the same transmission line. The 58' doublet consisting of two 29' sections resonates at about 8,000 kc and has a sufficiently broad frequency response to handle adequately frequencies in the 6,000 kc broadcasting band. The response of this doublet will also be peaked at 24 mc, the third harmonic frequency, but will be poor between about 11 and 20 mc. However, the second doublet consisting of the two 16.5' sections is peaked at about 14 mc and its response curve is high where that of the first doublet is low. The two response curves overlap and the total signal voltage is, at any frequency, the vector sum of the voltages developed by the two doublets. This overlapping or equalizing of the response over the frequency range is further facilitated by the cross-connecting of the left-hand 29' section to the right-hand

16.5' section, and the right-hand 29' section to the left-hand 16.5' section, as shown in the figure. This produces a resultant response curve which is high and in which the response is good between about 6 mc and 25 mc. This does not include the broadcast band. Methods of covering this band too will be discussed below under the heading of all-wave antennas.

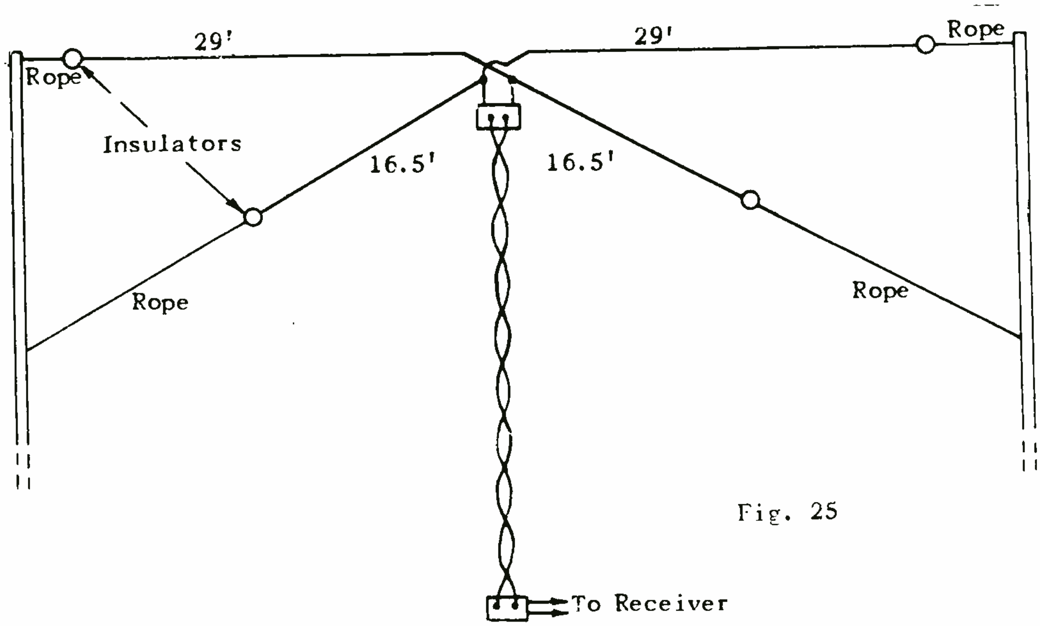


Fig. 25.—One type of antenna designed to cover a broad range of frequencies; called a double doublet.

RCA "SPIDERWEB" ANTENNA.—The RCA spiderweb antenna as shown in Fig. 26 was developed primarily to increase the frequency range of the double-doublet, and also to occupy somewhat less space. Even so it is regarded as somewhat too elaborate for ordinary apartment house installation, but is nevertheless superior to the simpler forms, and of value where maximum signal pick-up is of great importance, as is often the case in long distance short wave reception.

The array consists of five doublets, so peaked that by overlapping frequencies the entire high frequency band of modern all-wave receivers is covered. Doublet CC' is resonant to 6 mc; doublet AA' is resonant to 12 mc; doublet BB' is resonant to 18 mc; doublet DD' is resonant to 35 mc; doublet EE' is resonant to 60 mc. All except CC' connect through a transposition block in the center of the array and are thus connected to a short transmission line which extends down to the impedance matching transformer a few feet lower. CC' connects directly across the extremes of an autotransformer which, in addition to coupling the doublet to the transmission line, also adds necessary electrical length (loading) to this doublet. The entire length of the array from one extreme to the other is only 37 feet and the overall height is only 11 feet. Owing to the small vertical dimension, the vertical doublet DD' which resonates at 35 mc is also loaded.

MISCELLANEOUS TYPES.—In the range from about 40 mc and up, which embraces the f-m and television stations, various further combinations of dipoles are used. Instead of making the conductors larger in cross-section it is possible to obtain the same results (broadening of the frequency response) by using a number of smaller cross-section conductors in parallel. Three examples are shown in Fig. 27 (A), (B), and (C).

These have been designed especially for television receivers since they cover *simultaneously* the carrier and wide side bands characteristic of this type of signal. In (A) is shown a double V arrangement produced by fanning the ordinary dipole.

In (B) the conductors have been spread apart and are parallel. This makes the response even wider. Finally, in (C), a series of four half-wave fans are employed as shown in a series-parallel arrangement. The elements connected to either side of the transmission line are in parallel, and the group of such elements on one side is in series with that of the other side. This combination increases the received energy to approximately two and a half times that of a single element.

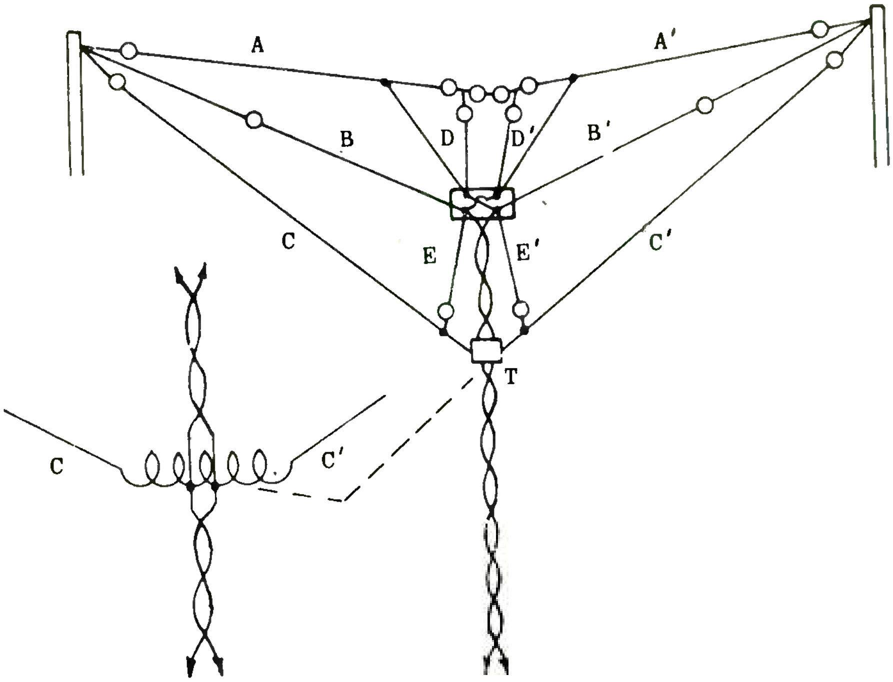


Fig. 26.—**R.C.A. Spiderweb antenna.**

If reception from one direction is required, the arrangements shown in Fig. 27 can be set so that their planes are perpendicular to the direction of pickup, and a re-

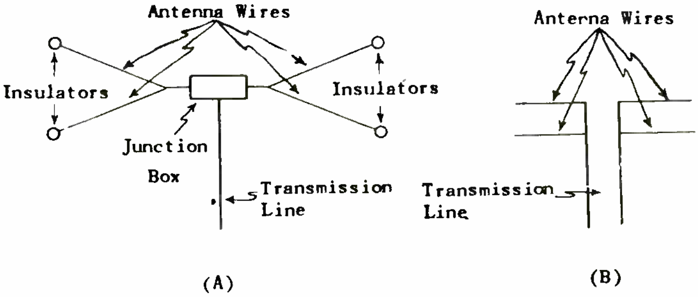


Fig. 27.—Various types of r-f antennas.

flector set up behind them. For example, for (C) of Fig. 27, twelve half-wave horizontal bars can be employed: Three behind each fan. The spacing between the antenna proper and the reflectors is ordinarily one-quarter wavelength.

The reflectors have some effect upon the selectivity curves of the antenna. In Fig. 28 is shown the measured selectivity curves of the arrangements shown in Fig. 27 (C) (with and without reflectors) and also (A), as well as those for a simple dipole. Note how much broader the response of the 4-fan arrangement of (C) is over that of the others, particularly the simple dipole. The reflector in general not only provides directivity, but approximately doubles the received energy.

The array of four half-wave fans and reflector was installed atop the 250-foot RCA antenna tower

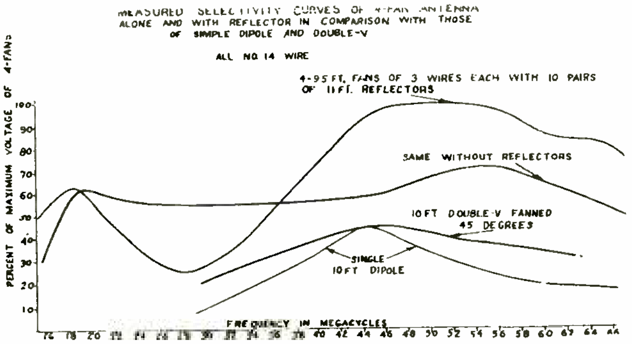


Fig. 28.—Selectivity curves for antennas shown in Fig. 27.

Holmes and Turner, "Simple Antennas and Receiver Input Circuits for Ultra-High-Frequencies"—Radio at Ultra-High-Frequencies, RCA Institutes' Technical Press.

at the New York World's Fair. The impedance from apex to apex of one pair of fans with reflector is 750 ohms at their resonant frequency. The vertical half-wave connectors can be regarded as forming two quarter-wave transmission lines connected at their center to the main transmission line. The usual design is to make the characteristic impedance of the connectors 750 ohms. Each quarter-wave portion therefore is terminated by its pair of fans in its characteristic impedance and presents this *same* value to the main transmission line. The two pairs of fans and associated quarter-wave portions present two 750 ohm resistances in parallel to the main line, or 375 ohms. If the main transmission line is designed to have a characteristic impedance of 375 ohms, it will be properly terminated by the combinations described above. Such a value of 375 ohms is perfectly practical for a transmission line of reasonable conductor size and spacing, and so no additional impedance transforming networks are required. This not only results in a simpler structure, but avoids the large variations in impedance with frequency which impedance transformers of the quarter-wave type and special networks produce.

THE FOLDED DIPOLE.—The impedance of an ordinary half-wave dipole is 73.2 ohms (in free space) and is too low for the ordinary two-wire line. While impedance matching devices, such as quarter-wave lines, can be used for single frequency operation, they are, as was mentioned, not particularly desirable for wide-band operation. A particularly simple modification of the dipole, known as the folded dipole, enables such transformation to be readily made. Note that here we are trying to obtain an impedance *higher* than the normal (73.2 ohms) for the antenna in order to couple the transmission line directly to the device, whereas in the preceding example the more complicated fan structure inherently gave too high an impedance (750 ohms) which had to be *reduced* to a reasonable value for a transmission line.

The folded dipole is shown in Fig. 29(A). Two half-wave dipoles closely spaced are connected to one another at their extremes. One of them is opened at the center in

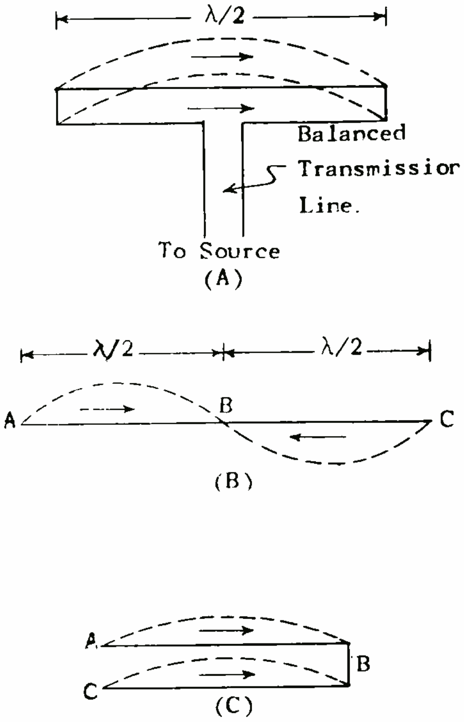


Fig. 29.—The folded dipole antenna.

order to be connected to a balanced transmission line. The pair may be regarded as a transmission line one wavelength long returned on itself. The current distribution for a wavelength line is shown in (B) and has been discussed in a previous assignment. If the line is folded back the arrangement shown in (C) is obtained. Note also that since A and C are current nodes, they may be connected together, and the generator inserted in the center of AB or CB. This gives the folded dipole arrangement shown in (A). From another viewpoint the two conductors can be regarded as being in parallel.

The close spacing between the two elements means that they radiate practically as one conductor. Let the current in either be I, and the radiation resistance of the combination be R_r. Then the power radiated is

$$P_r = (2\ I)^2\ R_r = 4\ I^2\ R_r$$

Since this power is supplied by the balanced transmission line, in which a current I is flowing, the resistance seen by the balanced line must be a value R' such that

$$I^2\ R' = P_r$$

From this and the preceding equation it is evident that

$$4\ I^2\ R_r = P_r = I^2\ R'$$

or

$$R' = 4\ R_r$$

This means that the resistance seen by the balanced line feeding the antenna is *four* times the radiation resistance of the antenna. If the latter is a half-wave in length, its radiation resistance is 73.2 ohms, and therefore the resistance seen by the line feeder is 4 × 73.2 = 293 ohms. The latter is a reasonable one for the characteristic impedance of a two-wire transmission line, or for a pair of concentric lines.

Thus the arrangement forms a radiating (or receiving) system and impedance transformer in one structure, and in addition has the merits of simplicity and mechanical strength. Various impedance transformations are possible. For example, if three wires are used, the line current is one-third the total, and the apparent resistance R' is then 9 times the radiation resistance R_r. It is not even necessary that three wires be used: If one has twice the cross-section of the other, and the latter is connected to the transmission line feeder, the same impedance transformation will be obtained. Thus by using two wires of different cross-sections, any impedance transformation is, at least, theoretically possible. This type of antenna is not only recommended for television, but for f-m purposes as well.

THE ALL-WAVE ANTENNA.—Many home receivers are designed to cover the standard broadcast band and one or more short wave bands. This means that the antenna must be designed to pick up the vertically polarized ground wave of standard broadcast frequency as well as possibly the direct wave (having either vertical or horizontal polarization) from an f-m transmitter, and the sky wave (having usually both types of polarization) of a distance short wave station. Such an antenna is known as an all-wave antenna. A usual frequency range is from 140 to 23,000 kc which covers the long wave, broadcast, and international short wave broadcast bands. However, the RCA spiderweb antenna, for example, can be made to cover a range up to 70 mc by the addition of an auxiliary kit, and it may be expected that antennas will be called upon to cover a range including television services.

For the broadcast band a vertical Marconi type antenna is desired; for the higher frequencies, a dipole, either vertical or horizontal, is indicated. In the case of long distance reception it has been mentioned that the received wave has both types of polarization regardless of the type radiated. This also appears to be true of line-of-sight transmission: Television signals radiated with horizontal polarization, for example, can be picked up by a *vertical* dipole. This may be due at least in part to the fact that a vertical dipole is not insensitive to horizontal polarization. Also reflections can produce horizontally polarized waves from vertically polarized waves. For the above reasons an all-wave antenna can be built by employing a *horizontal* dipole to a vertical grounded wire and to the receiver in such manner that at low frequencies the dipole acts as a flat top for the vertical grounded wire so that the combination is a Tee-type Marconi antenna, while at high frequencies the dipole acts as the pickup device, and the vertical grounded wire exhibits a *high reactance connection to ground* of negligible effect.

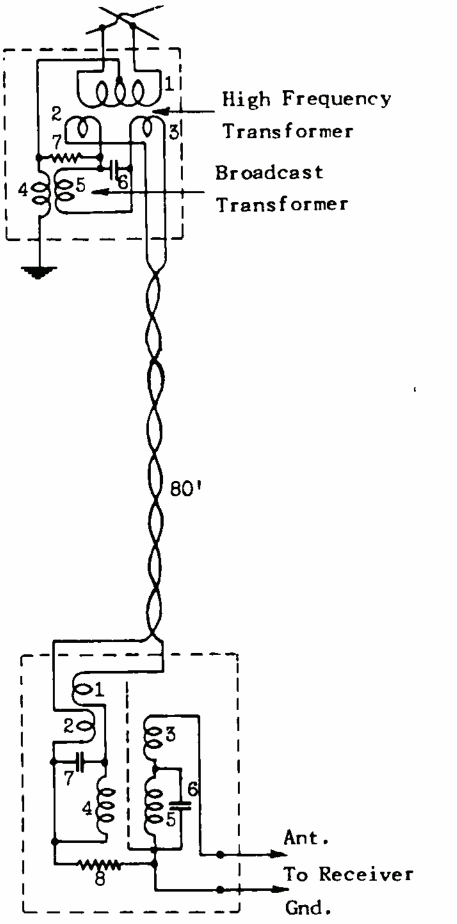


Fig. 30.—An all-wave antenna and matching network.

The above will be made clear by a specific example that also incorporates the noise-reducing features mentioned previously. In Fig. 30 is shown a doublet antenna connected to the primary 1 of a special high-frequency transformer. The latter is preferably mounted high up close to the antenna. The latter may be any one of the types previously described for high-frequency reception, and should be preferably of the large or multi-conductor type so as to have a low reactance and thus facilitate the design of the transformers required to operate with it over a wide frequency band.

The center tap of 1 is connected through primary 4 of the broadcast transformer to ground. The lead from 4 to ground may be quite long if the antenna is high up and may therefore exhibit resonances in the frequency range. To prevent this, a 500 ohm resistance is sometimes connected in series in this lead. In addition, resistor 7 is simply a static leak resistor to remove to ground static charges which may collect on the line.

The operation can best be understood by considering the action at low and at high frequencies. At low frequencies the coupling of primary 1 to secondaries 2 and 3 of the high frequency transformer in the antenna coupling unit is negligibly low and thus 1 merely connects the various portions of the doublet or more complex array in *parallel* to primary 4 and thence to the ground wire. The latter acts as a vertical Marconi antenna, as shown in Fig. 31, and the doublets as a flat top for the vertical portion. The only difference between this arrangement and that of an ordinary Marconi antenna for low-frequency pickup is that here the receiver is coupled through two sets of transformers to the antenna whereas ordinarily the vertical portion, in the form of a leadin, connects directly to the receiver input or antenna transformer. The arrangement shown in Fig. 31 evidently is preferable in that it enables the antenna to be located in a quiet place remote from the receiver and associated power circuits. The transmission line operates balanced to ground, so that noise picked up on its two leads cancels out.

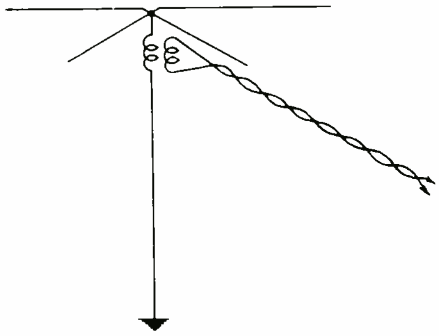


Fig. 31.—Simplified all-wave antenna.

Secondary 5 of the broadcast transformer connects to the transmission line through secondaries 2 and 3 of the high-frequency transformer, which have negligible reactance at low frequencies. At the same time capacitor 6 has a very high reactance at these low frequencies and thus constitutes a negligible *shunt* across 5.

In the same way secondaries 1 and 2 of the line-to-set coupling unit serve as mere connectors between the bottom ends of the transmission line and the broadcast primary 4, while 7 acts as a negligibly high shunt capacitive reactance across 4. Finally secondary 5 feeds signal to the receiver through high-frequency secondary 3 (of negligible reactance), and 6 is a negligibly high shunt across 5.

At high frequencies the vertical portion of the antenna is effectively isolated from the doublet above it by the high reactance of primary 4 of the antenna coupling unit. The doublet therefore operates essentially as an ungrounded Hertz antenna. Capacitor 6 in the antenna coupling unit serves to short out secondary 5, thus rendering the broadcast transformer inoperative, and at the same time serving to connect secondaries 2 and 3 in series to feed the balanced transmission line. In the same way capacitor 7 of the line-to-set coupling unit connects 1 and 2 in series to the other end of the transmission line, and simultaneously shorts out primary 4, while 6 shorts out secondary 5 and connects the lower end of 3 to the ground side of the receiver.

Note that high-frequency interference is mainly man-made and near the earth in contradistinction to low-frequency natural static which prevades the atmosphere. Moreover, high-frequency interference is mainly vertically polarized. For this reason a *horizontal* doublet, *high up in the air,* will pick up very little of the high-frequency interference. The balanced transmission picks up this interference equally on both conductors and thus does not pass it on to the receiver, just as for low-frequency static. For these reasons the antenna itself is practically free of noise pickup over the entire frequency band.

To summarize, we note that at low frequencies the antenna functions as a flat top, and is coupled to the receiver through broadcast transformer 4, 5 of the antenna coupling unit, the transmission line, and transformer 4, 5 of the line-to-set coupling unit; at high frequencies the antenna functions as a Hertz antenna isolated from ground by a high reactance, and is coupled to the receiver through high-frequency transformer 1, 2, 3, the same transmission line, and transformer 1, 2, 3, of the line-to-set coupling unit. At intermediate frequencies both portions of the antenna are active in picking up signal and both transformer sections of the antenna coupling and the line-to-set coupling units are operative. The transition in action is often around 5 mc, but this depends upon the frequency range to be covered.

It should be noted that no switches are required: the transition from high to low frequency action is automatically accomplished by the filter action of the components. At the same time, note the electrostatic shield in the line-to-set coupling unit. A comparison with Fig. 23 will show that this tends to minimize noise pickup from the power cord, as was described previously.

MODIFIED ALL-WAVE ANTENNAS.— The all-wave antenna system just described is one of the most elaborate and probably one of the best systems particularly if a more extended form of dipole array is employed. However, the system may be simplified appreciably without markedly affecting its all-wave pickup and noise-reducing qualities.

In Fig. 32 one possible modification is shown. An RCA Spider Web antenna and associated antenna transformer (compare with Fig. 26) may be used, or any other form, such as an ordinary doublet, may be used without the need for an antenna transformer.

Thus essentially only a line-to-set coupling unit is required. Moreover, the ground can be located close to the receiver. This is not an advantage; it is merely a concession to simplicity, and does permit noise to be picked up by the vertical portion of the antenna system. Hence there is no noise reduction of man-made static in the broadcast frequency range where the vertical portion is active as a pickup means. Note that the vertical portion is the transmission line whose two conductors act in parallel at low frequencies, and feed coil 3 (of negligible reactance at these frequencies) and capacitor 5 through the two halves, 1 and 2, of the high-frequency section. The two halves, 1 and 2, have negligible reactance at the lower frequencies, just as in the previous example. The receiver is energized by the voltage drop across capacitor 5 (of high reactance in this range) through the negligibly low reactance of secondary 4 of the high-frequency section. This action takes place at frequencies below 5 mc.

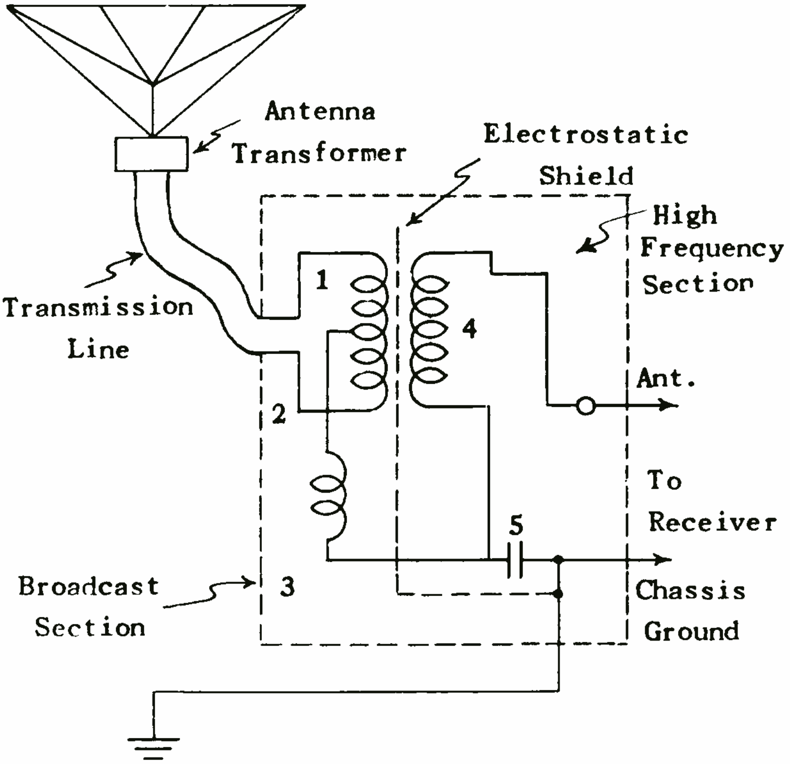


Fig. 32.—Modified form of an all-wave antenna.

At high frequencies (above 5 mc) the reactance of coil 3 is high, as is also the reactance of the transmission line when viewed as two conductors in parallel, and the two essentially isolate the antenna system from ground. The antenna therefore functions essentially as a Hertz system high up and remote from man-made static. It feeds its signal through the balanced transmission line to the primary halves 1 and 2 of the high frequency section. This induces a signal voltage in secondary 4, which is applied between the antenna and ground posts of the receiver, since the reactance of capacitor 5 in this frequency range is low, and hence the bottom end of 4 can be regarded as being substantially connected to the chassis ground.

It is felt that the magnitude of the man-made static in the broadcast range ordinarily is small compared to the natural static, and that a broadcast signal strong enough to override natural static will easily override man-made static. At the higher frequencies natural static is weak, but man-made static is not. Moreover, the signal picked up from a distant station will in general be weak, too, so that noise suppression in the high-frequency range is very desirable.

The arrangement shown in Fig. 32 will minimize the pickup of man-made static in the high-frequency range because of the following reasons:

1. The antenna, functioning as a dipole high above earth at the higher frequencies, picks up very little man-made static.

2. In addition, the transmission line itself, being balanced to ground, picks up such interference equally on both conductors and the effects are canceled out in the two halves, 1 and 2, of the primary of the high-frequency section.

3. The electrostatic shield serves to minimize line cord noise pickup so far as the high-frequency section is concerned in exactly the same manner as that described previously.

The installation is considerably simplified, too. Note that in the case of a simple doublet or similar arrangement, no antenna transformer is required and hence the antenna is easier to install. Further, the fact that the ground can be located next to the set simplifies matters in that a water pipe is usually near by, whereas a ground external to the dwelling usually requires a metal stake to be driven four or five feet into the earth. This feature may be of particular importance in the case of an apartment house.

Another modification, developed by V. D. Landon and J. D. Reid* of RCA is shown in Fig. 33. This arrangement has several features:

1. Only a line-to-set coupling unit is required, of course, in all cases, the receiver itself can have this coupling unit instead of its ordinary input unit, and this arrangement has been indicated in Fig. 33.

2. The above coupling unit does not require an electrostatic shield. Instead, a small trimmer capacitor, C, is employed to minimize noise arriving via the line cord. The cost of the coupling unit is thereby somewhat reduced. If one reflects that the home receiver business is the largest item in the radio industry, one can then appreciate that a small saving on an item is of importance, particularly in view of the great competition in this field. Indeed, from the economic viewpoint, a large and expensive change in the transmitters that results in a small saving in the

*Landon and Reid: "New Antenna System for Noise Reduction," I.R.E. Proc., March 1939.

cost of the receivers is justified in the broadcast field because of the relatively small number of transmitters and relatively large number of receivers involved.

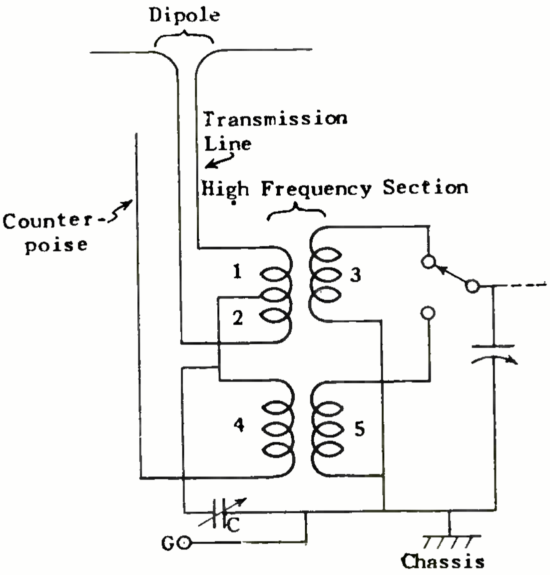


Fig. 33.—Another modified form of an all-wave antenna.

3. The counterpoise runs parallel to the transmission line and is spaced from it by about six inches. It is arranged to be about half the length of the transmission line plus ten feet. This means that three wires, one spaced from the other two, must be run from the dipole to the set. While this is a disadvantage, it will be observed that no ground is necessary, although terminal G can be connected to earth.

The theory of operation is as follows: At low frequencies the two sides of the transmission line act in parallel as a vertical Marconi antenna, and the dipole as a flat top. Signal is thus applied through the two halves, 1 and 2, of the primary of the high-frequency section to the top end of the broadcast primary 4. But the counterpoise applies a *similar signal*, of the same polarity, to the bottom end of 4. Hence the counterpoise *cancels* the signal pickup of the lower half of the transmission line acting as a vertical Marconi antenna.

It also cancels the noise pickup of the lower half of the line, and since this is the principal region where man-made static is present, it practically eliminates this type of noise pickup, *so that the combination does not have to be in a noise-free region.* The penalty for this is that only the top half of the transmission line is effective in picking up a signal, so that the effective height of the vertical antenna is reduced. This is not at all serious, however, since the receiver gain can be made adequate, and a broadcast signal strong enough to override set noise.

At the higher frequencies the top portion of the antenna functions as a Hertz dipole, and feed its signal through the balanced transmission line to the primary halves, 1 and 2, of the high-frequency section. If the coupling unit is an integral part of the receiver, a simple switch, as shown, can be made to select high-frequency secondary 3 or broadcast secondary 5 to feed the grid of the first tube. Such a switch would be part of a ganged switch for a two-band receiver. For an all-wave receiver, secondary connections involving a shunt capacitor across the broadcast secondary could be employed, as in Fig. 30, and the switch eliminated.

The noise pickup in this frequency range is low owing to the elevated location of the dipole and the balanced transmission line employed, just as was the case in the previous examples. The minimizing of line cord noise has still to be explained, however. It was pointed out that this is accomplished by the use of a trimmer capacitor C instead of an electrostatic shield.

The action is as follows: Both the counterpoise and the antenna have capacities to *true* ground, and the latter is evidently the greater since the antenna is the longer of the two. Furthermore, the top end of primary coil 4 and its bottom end have capacities to the chassis. The trimmer capacitor C artificially increases the capacity C_1 of the top end of coil 4 over that of the bottom end C_2, and the essential features of the circuit—so far as power line noise is concerned—are represented in Fig. 34. The power line noise appears as a voltage between the chassis and true ground.

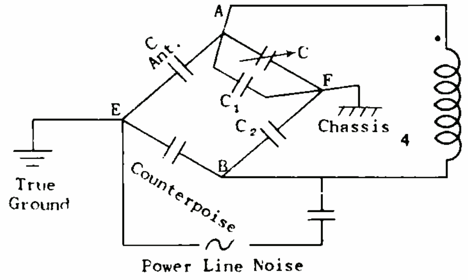


Fig. 34.—Capacity bridge representation of the noise balancing properties of Fig. 33.

The various capacitors form a kind of capacity Wheatstone bridge. This is balanced, i.e., no noise voltage appears across terminals A B regardless of how much is impressed across E F if:

$$\frac{C + C_1}{C_2} = \frac{C\,(\text{Ant.})}{C\,(\text{Counterpoise})}$$

By adjustment of C, the left-hand ratio can be made equal to the right-hand ratio, and the balance obtained. This balance, unfortunately, does not hold absolutely true for all frequencies because the impedance of the antenna and of the counterpoise do no remain capacitive as one goes up in frequency, and so best balance is maintained at the lower frequencies, below the fundamental frequency of the antenna where its inductance becomes important.

For ordinary practical antenna lengths the balance is satisfactory in the broadcast band, and at higher frequencies, around 5 mc, some noise may be picked up, while at still higher frequencies the antenna begins to function primarily as a dipole, and noise pickup is minimized once more. It is evident that if the primary coil capacities to the chassis, C_1 and C_2, are made small, so that C can be small and yet maintain the ratio given above, then the reactance between A and F, and between B and F will be high, and very little noise currents entering at E and F can get into A and B and thence into primary coil 4. Thus, if C_1 and C_2 are small, even at frequencies where the balance is poor, little noise voltage will get into the receiver.

The device can also be used with receivers having the ordinary antenna input transformer whose primary is grounded to the chassis. In this case the coupling device should have a secondary circuit similar to that shown in Fig. 30. Finally, it is to be noted that the coupling device can be used with an ordinary antenna, such as of the inverted L-type. The connections are shown in Fig. 35. In this case the low frequencies pass through primary half 1 with little opposition and thence through broadcast primary 4, where they induce a current in secondary 5. Owing to the poor efficiency of transformer 1, 2, 3 at the lower frequencies, practically no voltage is induced in secondary 3.

At the high frequencies, the antenna currents pass through 1, where they induce a voltage in 3, and then pass through the low reactance path of C to ground. Of course no noise reduction is obtained with this simpler type of antenna and connection.

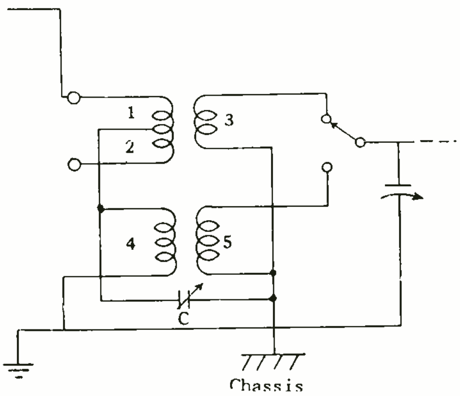


Fig. 35.—Coupling network of Fig. 33.

AUTOMOBILE ANTENNAS.—Automobile antennas in the past have been located in various places on the car. One type was a wire netting in the top. While this was very satisfactory, it became obsolete with the advent of the all-metal top.

Another location is beneath the running boards. Since the ground connection of the receiver is connected to the car body, it is desirable to get the antenna as far from the car structure as possible. At the best with an underbody antenna this can be only a very few inches and even then the arrangement is bad from a mechanical viewpoint because of the requirement of adequate road clearance, especially in the case of deep ruts.

On such system antenna is shown in Fig. 36. The two loops of tubing on each side of the car are simply in series to add length for increased capacity to the car body, just as in the case of an ordinary flat top antenna.

The particular points in the design of such an antenna are the lengths of the sections and the point at which the connection to the receiver is taken off. The length is made such that each section forms a doublet for the predominating ignition noise frequency and the entire system tied together should thus have an effective electrical length of one wavelength. The receiver lead is then tapped off at an ignition voltage nodal point. With the two halves of each section folded back on each other, the effect is very similar to that of the two wire tuned transmission line which the pickup at the resonant frequency tends to cancel out in the two parallel wires, this effect adding to the fact that the receiver connection is made at a noise voltage nodal point. Of course for signals in the broadcast frequency range the system is simply an aperiodic conductor.

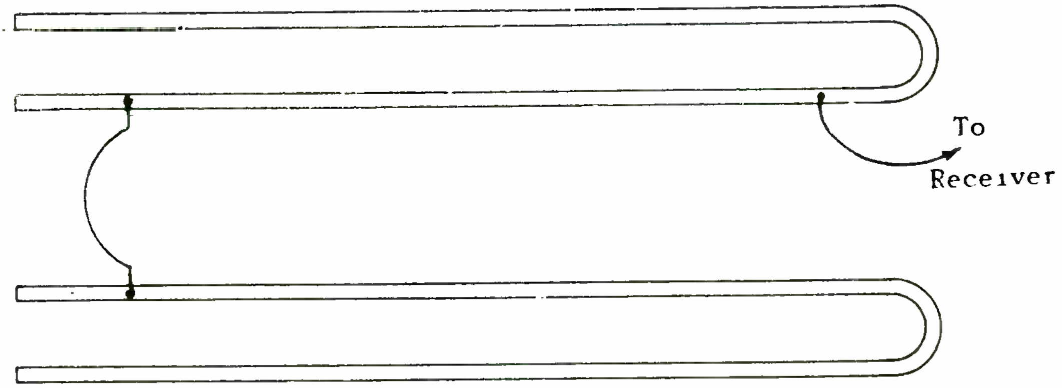
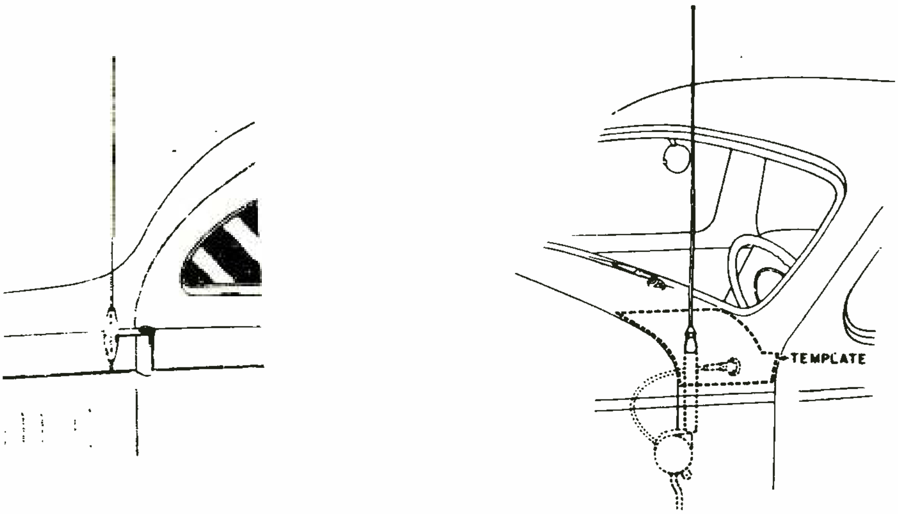


Fig. 36.—One type of automobile antenna to be installed beneath the running board.

While in many cases a satisfactory signal-to-noise ratio may be obtained with this type of antenna, the fact remains that not only is the location under the running boards bad mechanically, but the antenna is also subject to pickup of wheel static, i.e., disturbances due to the static charges that accumlate on the car from the contact of the tires with the road.

A better type of antenna is the simple vertical antenna extending about three feet above the metal top. Other locations are the upper front door hinge, Fig. 37(A), or on the side cowl, as in Fig. 37(B). According to J. A. Doremus in an article entitled "Planning A V-H-F Communications System" appearing in Electronics magazine for September 1943, the best location, particularly for a *transmitting* antenna, as in police radio systems, is in the center of the top of the car. The antenna then emits *a greater signal in all directions* than an antenna mounted on the rear of the car, in which case radiation towards the front of the car is three or four times that in the opposite direction. Nevertheless, for ordinary *receiving* purposes, a location near the driver is favored, such as that shown in Fig. 37, especially if the antenna system is designed to be retractable from the inside of the car.



(A) (B)

Fig. 37.—Two examples of whip antennas.

The short length of the antenna produces two major problems in the broadcast frequency range. The first is that of effective height. Tests made by Foster and Mountjoy and described in the RCA Review for January 1939 in an article entitled "Measurement of Effective Height of Automobile Antennas" indicate that most antennas have an effective height less than 14.05 cm or 5.53 inches!

It will be recalled from an earlier assignment on transmitting antennas that for a simple vertical antenna much less than $\lambda/4$, the current distribution is approximately triangular, being maximum at the base and zero at the top. The radiation from such an antenna with variable current magnitude along its length is the same as that from an antenna of *half the height*, but with *a constant current magnitude* along its length equal to the maximum value of current (at the base) of the actual antenna. This defines the *effective height* as half of the actual height.

The above derivation given in an earlier assignment was based on.

the vertical antenna being located above a plane, perfectly conducting earth. The automobile antenna is close to the metal body of the car, of irregular shape, and in this case the effective height comes out to be but a few inches as mentioned previously.

Such an antenna can develop but a small signal voltage. For example, if the field strength is 100 μ-volts per meter, and the effective height of the antenna is but 14 cm = .14 meters, then the signal developed by the antenna is only

$$100 \times .14 = 14\ \mu\text{-volts}$$

This might appear to be adequate for a broadcast receiver, but it must be remembered that this is the voltage developed or apparently generated by the antenna, and is greater than that actually delivered to the input terminals of the receiver. This will be discussed below. However, another factor must be taken into account, and this is the noise field around the car.

One source of noise has already been mentioned: wheel static. For an antenna mounted above the car body this does not appear to be a serious source of noise, probably because of the shielding effect of the car body itself. There is, however, another source of disturbance that is important, namely, ignition noise. The ignition system acts like a series of spark transmitters, and although the inductances and capacities involved in the oscillating circuits are small, and hence the radiated frequencies high, there is nevertheless appreciable disturbance even at the broadcast frequencies, particularly in close proximity to the car.

At first this form of disturbance was minimized through the use of suppressors: High resistances (10,000 to 25,000 ohms) inserted in series with the spark plugs to damp out the oscillations and further prevent the high frequency currents from flowing along the high tension leads and radiating disturbances from them. Such suppressors tend to affect the engine performance, and modern cars have their ignition systems so well shielded that at most but one suppressor on the distributor is all that is required.

It is also important that all electrical leads, metal rods, and tubing, such as the fuel line, be at r-f ground potential. This is accomplished by grounding such parts to the chassis by copper strap or braid, or—if the wire is at a d-c potential to ground, by shielding it and grounding the shield, or by grounding the lead itself through a small by-pass capacitor (about 0.1 mf or larger). Interference originating at one point of the car may travel a considerable distance along the wiring, for example, and be reradiated from the latter at various points. If the source of the interference is isolated, as may be done, for example, by disconnecting the leads from the source and noting the cessation of noise in the receiver, then it is possible to prevent the interference from being reradiated by the use of a series r-f inductance between the noise source and the wiring, together with a by-pass capacitor from the source to ground.

It is evident that the problem is the usual one of obtaining a high signal-to-noise ratio aggravated by the high noise level in and around the car, and by the proximity of the antenna to the car.

Wheel static is apparently caused by the static charges of the tires leaking through the variable resistance path between the ball races and the balls of the wheel bearings to the body of the car. Since the front wheels run free on such bearings and have no other connection to the body, it is to be expected that they would be the worst offenders. The remedy is to ground the wheels to the supporting axles more thoroughly. A typical method is through the use of springs, known as Wheel Static Eliminators, Fig. 38, which press between the hub cap and the supporting axle in each front wheel and thus ground the wheels. The rear wheels may also require grounding owing to the static charges produced by the friction in the brake drums.

Fig. 38.—Spring-used as a wheel static eliminator.

When the noise has been reduced to an acceptably low level, the problem of conveying the signal to the set remains to be solved. The leadin wire can pick up interference just as in the case of the household receiver, and so should be as short as possible. A whip antenna usually provides the shortest leadin to the receiver.

The leadin should be shielded and the shielding grounded. This may seem surprising to the student in view of what was said previously in this assignment as to the lack of value of such shielding in the case of the ordinary Marconi antenna. There, however, the leadin was the source of the signal pickup, whereas here the leadin is *inside of the car body* and hence shielded by the metal body from *external signals, but not from internal ignition interference etc.* Therefore shielding here is of value.

Such shielding, however, increases the capacity of the leadin to ground. The equivalent circuit is as shown in Fig. 39. Here e_g represents the voltage developed in the antenna by the incident radio wave, and C_1 its internal impedance as viewed from the bottom end of the antenna. As explained previously, a short antenna (much less than $\lambda/4$) appears as a capacity and resistance in series in which the capacitive reactance is far greater than the

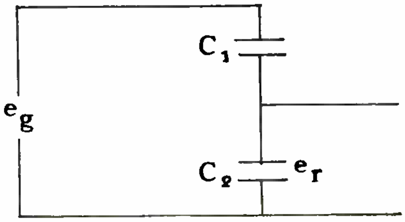


Fig. 39.—Equivalent circuit for the leadin capacity.

resistive component, particularly if the antenna is very short. Since a high capacitive reactance corresponds to a small capacitor, C_1 is small—in the case of a whip antenna it may be as low as 20 mmf and possibly even less.

The capacity of the leadin is represented by C_2. If this is large, its reactance is small and hence the voltage delivered to the receiver, e_r, will be but a fraction of e_g, in itself small. Specifically e_r is to e_g as the reactance of C_2 is to the reactance of C_1 and C_2 in series, i.e., that of a capacitor of value:

$$\frac{C_1 C_2}{C_1 + C_2}$$

Thus

$$\frac{e_r}{e_g} = \frac{1/\omega C_2}{1/\omega \; \dfrac{(C_1 \; C_2)}{(C_1 + C_2)}} = \omega \frac{\dfrac{C_1 C_2}{C_1 + C_2}}{\omega \, C_2} = \frac{C_1}{C_1 + C_2}$$

or, multiplying through by e_g, we have

$$e_r = e_g \frac{C_1}{C_1 + C_2}$$

It is evident that if C_2 is much greater than C_1,

$$\frac{C_1}{C_1 + C_2}$$

will be a very small fraction, i.e., e_r will be a very small fraction

$$\left(\frac{C_1}{C_1 + C_2}\right)$$

of e_g. If a reasonable amount of signal e_r is to be delivered to the receiver, either C_2 must be small, or C_1 must be comparable to C_2. In the case of a top antenna or an underbody (running board) antenna C_1 may be as high as 500 mmf; an average value being about 160 mmf. The leadin and the input circuit can be readily designed to extract the maximum signal e_r from such an antenna, and hence such an antenna may show up to advantage in comparison with a low capacity antenna of the same effective height.

In the case of the whip antenna it is more difficult to design the input circuit owing to the low value of the antenna's internal capacity C_1. The leadin should be a low capacity type of cable; one whose shield is of relatively large diameter and thus spaced by an appreciable distance from the inner conductor. Fortunately, as mentioned previously for the whip antenna, the leadin can usually be very short, and its capacity therefore low.

The capacity of an antenna can be increased, and the reactance made low by increasing the cross section of the antenna, as has been mentioned previously. In the case of a wire mesh antenna in the top of the car, or one under the running boards such large cross section exists inherently in the structure, but in the case of a whip antenna, a large cross section might make the whip too rigid and cause it to break if it struck an overhead obstruction. Hence it is advisable to design the input circuit of the receiver to have a high impedance in order to operate properly from this type of antenna.

A typical coupling circuit is shown in Fig. 40. Inductances L_1 and L_2 are for the purpose of canceling out the capacitive reactance of the antenna, thus lowering its apparent internal impedance and permitting more current to flow into L_3, the tunable antenna transformer or choke. This increases the signal voltage across L_3, to which the control grid of the first tube is connected as shown.

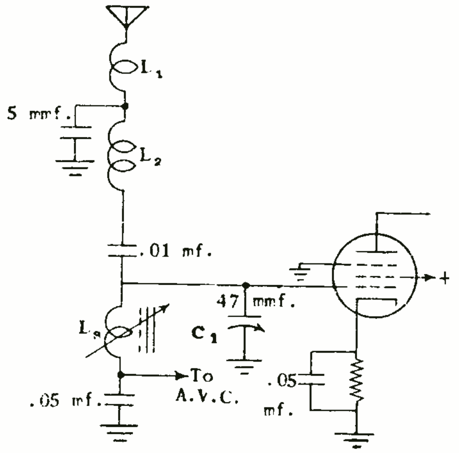


Fig. 40.—Typical coupling circuit for auto radios.

The trimmer capacitor C_1 is used to adjust the antenna circuit for various antennas. The method is to set the tuning control (which varies L_3) to a weak station on a frequency between 1200 and 1400 kc. Then C_1 is adjusted until maximum output with the given antenna is obtained. The action of C_1 is to draw a leading current, while L_3 draws a larger lagging current. The line current flowing into the two from L_2 is therefore the difference between the two, and while lagging, is less than that in L_3 by the amount of leading current drawn by C_1. The effect is therefore to make the parallel circuit consisting of L_3 and C_1 appear as a *higher inductance* than L_3 itself. Thus C_1 can act as a sort of padder adjustment for L_3, and adjust the apparent inductance to resonate with the antenna capacity and L_2. (The 5 mmf capacitor in a similar manner tends to increase the apparent inductance of L_2 and L_3).

In tuning, L_3 is varied to maintain the above series resonance all over the broadcast band. Inductive tuning is employed to a large extent in automobile radios because it is not only very well suited to push button tuning, but maintains its adjustments better under vibration.

RADIO WAVE PROPAGATION RECEIVING ANTENNAS—PART II

EXAMINATION

1. What is the optimum relationship between the projected and actual lengths of an inclined antenna to give maximum pickup?

2. How is the angle of maximum pickup affected by the wavelength of the received energy in the case of a V-antenna?

3. The wire length of either side of a given V- antenna is 8λ. Find the optimum angle of inclination ϕ, and find the value of the modified termination if the characteristic impedance of the line is 600 ohms.

4. (A) Name three advantages of a rhombic antenna over a V-antenna.

(B) In what position is a rhombic antenna normally used? Why?

5. A horizontally polarized wave from a distant station arrives at the receiving location at a sky wave angle of 15°. The wavelength is 15 meters. Design the rhombic antenna if the height must not exceed 11.25 meters, and the direction of maximum pickup is to be that of the sky wave angle, or 15°.

6. (A) Why are the primary and secondary coils of the antenna transformer in a broadcast receiving set loosely coupled to one another?

(B) What is the function of the open-circuited turn between the primary and secondary coils.

7. (A) In the case of an ordinary Marconi type antenna, what benefit is derived from the use of a flat-top?

(B) Why should the pickup from the lower portion of the leadin be eliminated in the standard broadcast range?

8. (A) From what source does most external noise reach a receiver?

(B) How is a short wave antenna made to cover a wide range of frequencies?

9. (A) How is a television antenna designed so as to accomodate *simultaneously* a carrier and a wide range of side bands?

(B) What is the fundamental difficulty in the design of an automobile antenna?

10. (A) What effect has a high capacity leadin, particularly when a whip antenna is employed?

(B) What are the advantages of inductive tuning over capacitive tuning?